# Activity Report 2015

# Team Chroma

## Cooperative and Human-aware Robot Navigation in Dynamic Environment

Inria teams are typically groups of researchers working on the definition of a common project, and objectives, with the goal to arrive at the creation of a project-team. Such project-teams may include other partners (universities or research institutions).

RESEARCH CENTER
**Grenoble - Rhône-Alpes**

THEME
**Robotics and Smart environments**

# Table of contents

# Team Chroma

*Creation of the Team: 2015 March 01*

**Keywords:**

**Computer Science and Digital Science:**

5.10.2. - Perception
5.10.3. - Planning
5.10.5. - Robot interaction (with the environment, humans, other robots)
5.10.6. - Swarm robotics
8.5. - Robotics
8.7. - AI algorithmics

**Other Research Topics and Application Domains:**

5.2.1. - Road vehicles
5.6. - Robotic systems
7.1.2. - Road traffic
8.4. - Security and personal assistance

*The Chroma team is distributed on two sites : Montbonnot Inria Centre and CITI laboratory at INSA de Lyon.*

# 1. Members

**Research Scientists**

Christian Laugier [Inria, Senior Researcher, HdR]
Agostino Martinelli [Inria, Researcher]
Alejandro Dizan Vasquez Govea [Inria, Starting Research position, until Dec 2015]

**Faculty Members**

Olivier Simonin [Team leader, INSA Lyon-CITI, Professor, HdR]
Anne Spalanzani [UPMF, Associate Professor, from Dec 2015, HdR]
Jilles Dibangoye [INSA Lyon-CITI, Associate Professor]
Jacques Saraydaryan [CPE Lyon-CITI, Associate Professor, associate member from Sep. 2015]
Fabrice Valois [CPE Lyon-CITI, Associate Professor, associate member from Sep. 2015]

**Engineers**

Amaury Nègre [SED, CNRS]
Jean-Alix David [Inria]
Guillaume Fortier [Inria]
Jan Michalczyk [Inria]
Lukas Rummelhard [Inria]
Procopio Silveira Stein [Inria, until Nov 2015]
Trung Dung Vu [Inria, until Jun 2015]

**PhD Students**

Mathieu Barbier [Renault, granted by CIFRE]
Mihai-Ioan Popescu [INSA Lyon]
Stefan Chitic [INSA Lyon]
Tiana Rakotovao Andriamahefa [CEA]
David Sierra Gonzalez [Inria]

**Administrative Assistants**

Isabelle Allegret [Inria, until Jun 2015]
Marina Da Graca [Inria, from Sep 2015]
Myriam Etienne [Inria, until Aug 2015]

**Others**

Jonathan Cohen [Univ. Lyon I, M2 internship, from Feb 2015 until Jun 2015]
Nishant Jain [Inria, M2 internship, from Feb 2015 until Jun 2015]
Jacques Kaiser [Inria, M2 internship, from Feb 2015 until Jul 2015]
Martin Pugnet [INSA Lyon, M2 internship, from Feb 2015 until Jun 2015]
Stephanie Lefevre [UC Berkeley]
Jerome Lussereau [CNAM thesis (bourse Fongecif)]
Mathias Perrollaz [Bluebotics Lausanne]

# 2. Overall Objectives

## 2.1. Origin of the project

The Chroma group was created in the beginning of year 2015 (March). It regroups researchers who address perception and navigation issues in mobile robotics and who share common approaches which mainly relates to the field of artificial intelligence. The group is gathering some members of the eMotion Inria project-team led by Christian Laugier (DR1) and of teacher-researchers of the CITI Lab. in Lyon working in the robotic group led by Olivier Simonin (Prof.). The team is distributed on two sites, the Centre Inria Grenoble and the CITI Lab. in Lyon.

The Chroma group was initially composed of O. Simonin (Prof. Insa Lyon), C. Laugier (DR1 Inria), J. Dibangoye (MCF. Insa Lyon), A. Martinelli (CR1 Inria) and D. Vasquez (SRP Inria). On December 1, 2015, Anne Spalanzani (MCF Univ. Grenoble, HDR) has joined the group (she was previously in Prima and eMotion Inria teams). In January 2016, Dizan Vasquez leaves the group to join the Apple company.

## 2.2. Overall Objectives

The overall objective of Chroma team is to address fundamental and open issues that lie at the intersection of the emerging research fields called “Human Centered Robotics" [1] and “Multi-Robot Systems (MRS)" [2].

**More precisely, our goal is to design algorithms and develop models allowing mobile robots to navigate and operate in dynamic and human-populated environments. Chroma is involved in all decision aspects pertaining to mono- and multi-robot navigation tasks, including perception and motion-planning.**

The general objective is to build robotic behaviors that allow one or several robots to operate and cooperate safely among humans in partially known environments, where time, dynamics and interactions play a major role. Recent technological progress on embedded computational power, on sensor and communication technologies, and on miniaturized mechatronic systems, make the required technological breakthroughs possible (including from the scalability point of view).

Chroma is positioned in the third challenge of the **Inria 2013-2017 Strategic Plan "Interacting with the real and digital worlds: interaction, uses and learning"**.

[1] Montreuil, V.; Clodic, A.; Ransan, M.; Alami, R., "Planning human centered robot activities," in Systems, Man and Cybernetics, 2007. ISIC. IEEE International Conference on , vol., no., pp.2618-2623, 7-10 Oct. 2007

[2] IEEE RAS Multi-Robot Systems http://multirobotsystems.org/

## 2.3. Research themes

Our approach for addressing the previous challenge is to bring together probabilistic methods, planning techniques and multi-agent decision models. This will be done in cooperation with other disciplines such as psycho-sociologists for the purpose of taking into account human models. Two main research themes of robotic navigation are addressed : i) understanding complex scenes from sensors information ii) single and multi-robot planning for motion in human-populated and dynamic environments. Next, we elaborate more about these two research axes.

- **Perception and Situation awareness in human-populated environment**. The main problem is to understand complex dynamic scenes involving mobile objects and human beings, by exploiting prior knowledge and a stream of perceptual data coming from various sensors. Our approach for solving this problem is to develop three complementary problem domains:
  - **Sensor Fusion**: acquire a deep understanding on several sensor fusion problems and investigate their observability properties in the case of unknown inputs.
  - **Bayesian Perception**: How to take into account prior knowledge and uncertain sensory data in a dynamic context?
  - **Situation awareness** : How to interpret the perceived scene and to predict their likely future motion (including near future collision risk) ?
- **Scaling-Up Single and Multi-Robot Motion-Planning**. The challenge is to build models allowing robots to move and coordinate efficiently in dynamic environments while considering the social rules of human beings evolving and interacting with them. This requires scalable algorithms able to manage large multi-robot systems and to adapt to the dynamics. We address this problem by considering two complementary challenges :
  - **Single-robot motion-planning in human-populated environment.** How to plan trajectories that take into account the uncertainty of human-populated environments and that can respect the social rules of humans ? Such a challenge requires human behavior models and planning algorithms that take into account them and the dynamic of the environment (perceived following first research theme).
  - **Multi-robot motion-planning in complex environments.** The goal of this axis is to develop models and algorithms that provide both scalability and performance guarantees in real-world robotic systems. Our methodology builds upon complementary advantages of two orthogonal approaches, Multi-Agent Sequential Decision Making (MA-SDM) and Swarm Robotics (SR).

The Chroma project is also concerned with applications and transfer of the scientific results. Chroma have currently projects developed with industrial and start up partners. Our main application domains concern autonomous vehicles (in cooperation with Renault and Toyota), aerial robots for surveillance tasks and services robotics. These collaborations and transfers are presented later in the document.

# 3. Research Program

## 3.1. Perception and Situation Awareness

**Robust perception and decision-making in open and dynamic environments populated by human beings is an open and challenging scientific problem**. Traditional perception techniques do not provide an adequate solution for this problems, mainly because such environments are uncontrolled [3] and exhibit strong constraints to be satisfied (in particular high dynamicity and strong uncertainty). This means that the proposed solutions have to simultaneously take into account characteristics such as real time processing, temporary occultations, dynamic changes or motion predictions; these solutions have also to include explicit models for reasoning about uncertainty (data incompleteness, sensing errors, hazards of the physical world).

[3] partially unknown and open

### 3.1.1. Sensor fusion

In the context of autonomous navigation we investigate sensor fusion problems when sensors and robots have limited capacities. This relates to the general study of the minimal condition for observability.

A special attention is devoted to the fusion of inertial and monocular vision sensors. We are particularly interested in closed-form solutions, i.e., solutions able to determine the state only in terms of the measurements obtained during a short time interval. This is fundamental in robotics since such solutions do not need initialization. For the fusion of visual and inertial measurements we have recently obtained such closed-form solutions in [41] and [44]. This work is currently supported by our ANR project VIMAD [4].

We are also interested in understanding the observability properties of these sensor fusion problems. In other words, for a given sensor fusion problem, we want to obtain the physical quantities that the sensor measurements allow us to estimate. This is a fundamental step in order to properly define the state to be estimated. To achieve this goal, we apply standard analytic tools developed in control theory together with the concept of *continuous symmetry* recently introduced by the emotion team [40]. In order to take into account the presence of disturbances, we introduce general analytic tools able to derive the observability properties in the nonlinear case when some of the system inputs are unknown (and act as disturbances).

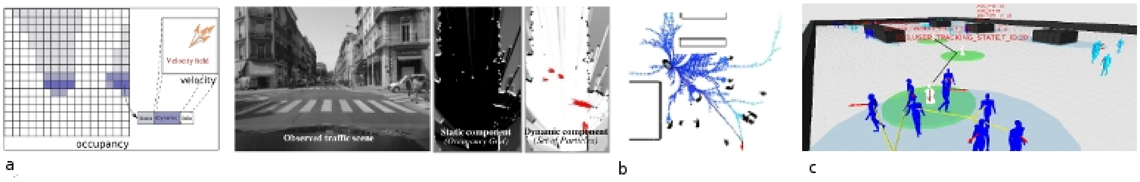



*Figure 1. Illustrations a) HSBOF model b) Risk-RRT planning with humans c) simulating humans and robots.*

### 3.1.2. Bayesian perception

In previous work carried out in the eMotion team, we have proposed a new paradigm in robotics called "Bayesian Perception". The foundation of this approach relies on the concept of "Bayesian Occupancy Filter (BOF)" initially proposed in the PhD thesis of Christophe Coué [28] and further developed in the team [36]. The basic idea is to combine à Bayesian filter with a probabilistic grid representation of both the space and the motions, see illustration Fig. 1.a. This model allows the filtering and the fusion of heterogeneous and uncertain sensors data, and 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. Current and future work on this research axis addresses two complementary issues:

- Development of a complete framework for extending the Bayesian Perception approach to the object level, in particular by integrating in a robust way higher level functions such as multiple objects detection and tracking or objects classification. The idea is to avoid well known data association problems by both reasoning at the occupancy grid level and at object level (i.e. identified clusters of dynamic cells) [47].
- Software and hardware integration to improve the efficiency of the approach (high parallelism), and to reduce important factors such as ship size, price and energy consumption. This work is developed in cooperation with the CEA LETI and the project Perfect of the IRT nanoelec. The validation and the certification issues will also be addressed in the scope of the ECSEL ENABLE-S3 project (to be started in 2016).

[4]Navigation autonome des drones aériens avec la fusion des données visuelles et inertielles, lead by A. Martinelli, Chroma.

### *3.1.3. Situation Awareness & Bayesian Decision-making*

Prediction is an important ability for navigation in dynamic uncertain environments, in particular of the evolution of the perceived actors for making on-line safe decisions (concept of "Bayesian Decision-making"). We have recently shown that an interesting property of the Bayesian Perception approach is to generate short-term conservative [5] predictions on the likely future evolution of the observed scene, even if the sensing information is temporary incomplete or not available [46]. But in human populated environments, estimating more abstract properties (e.g. object classes, affordances, agents intentions) is also crucial to understand the future evolution of the scene. Our current and future work in this research axis focus on two complementary issues :

- Development of an integrated approach for "Situation Awareness & Risk Assessment" in complex dynamic scenes involving multiples moving agents (e.g vehicles, cyclists, pedestrians ...) whose behaviors are most of the time unknown but predictable. Our approach relies on combining machine learning to build a model of the agent behaviors and generic motion prediction techniques (Kalman-based, GHMM [57], Gaussian Processes [52]). In the perspective of a long-term prediction we will consider the semantic level [6] and planning techniques developed in the following Section.
- Development a new framework for on-line Bayesian Decision-Making in multiple vehicles environments, under both dynamic and uncertainty constraints, and based on contextual information and on a continuous analysis of the evolution of the probabilistic collision risk. Results have recently been obtained in cooperation with Renault and Berkeley, by using the "Intention / Expectation" paradigm and Dynamic Bayesian Networks [38], [39]. This work is carried out through several cooperative projects (Toyota, Renault, project Prefect of IRT Nanoelec).

## 3.2. Single and Multi-robot Motion-Planning

Motion-planning is a classic and large problem of navigation robotics. In Chroma it is considered in its broad definition, that is **all tasks that require one or several robots to move and to interact autonomously**. In this context, we aim at designing navigation models and strategies that scale up with the complexity of the robotic system, the environment, and the social rules of the human beings that operate and may interact. This research axis is divided in two complementary challenges: (a) single-robot motion-planning in human-populated environment; and (b) multi-robot motion-planning in complex environments.

### *3.2.1. Single-robot motion-planning in human-populated environment*

Motion planning in dynamic and human-populated environments defines a central challenge of robotics. Unlike static or controlled environments [7] where global path planning approaches are suitable, dealing with highly dynamic and uncertain environments requires to integrate the notion of risk. This risk can be computed by methods proposed in section 3.1.3. Then we examine how motion planning approaches can integrate this risk in the generation and selection of the paths [51] (see Figure 1.b for illustration).

Hovever, robots are expected to share the physical space with humans. Hence, robots need to take into account the presence of humans and to behave in a socially acceptable way. Their trajectories must be safe but also predictable. Their behavior should follow social conventions, respecting proximity constraints, avoiding people interacting or joining a group engaged in conversation without disturbing. For this purpose, we propose to integrate semantic knowledge [8] and psycho-social theories of human behavior [9] [10] in the navigation framework we have developped for a few years through our Risk-based navigation algorithms [32], [51], [56].

[5] i.e. when motion parameters are supposed to be stable during a small amount of time
[6] knowledge about agents' activities and tasks
[7] known environment without uncertainty
[8] B. Kuipers, The Spatial Semantic Hierarchy, Artificial Intelligence, Volume 119, Issues 1–2, May 2000, Pages 191-233
[9] Gibson, J. (1977). The theory of affordances, in Perceiving, Acting, and Knowing. Towards an Ecological Psychology. Number eds Shaw R., Bransford J. Hoboken,NJ: John Wiley & Sons Inc.
[10] Hall, E. (1966). The hidden dimension. Doubleday Anchor Books.

We also started to examine how motion planning approaches can help to predict the motion of rational physical agents (humans), based on the hypothesis that behavior –and, eventually, interactions– can be modeled through a cost function. This led us to explore mechanisms to learn that cost function from observed human behavior such as Inverse Reinforcement Learning [11] [55]. Research in Chroma will continue in this direction with the ambition of generalizing this methodology of learning human motion in order to optimize robot motions and their interactions with humans.

### *3.2.2. Multi-robot motion-planning in complex environments.*

In his reference book *Planning algorithms* [12] S. LaValle discusses the different dimensions that made the motion-planning problem complex, which are the number of robots, the obstacle region, the uncertainty of perception and action and the allowable velocities. In particular, it is emphasized that complete algorithms require at least exponential time to deal with multiple robot planning in complex environments, preventing them to be scalable in practice (p. 320). Moreover, dynamic and uncertain environments, as human-populated ones, expand this complexity. In this context, developping simulators can help to analyze this complexity and to define planning strategies, as we done in [11] [45], as illustrated in Fig. 1.c.

Over the past few years, our attempts to address multi-robot motion-planning are mainly due to Multi-Agent Sequential Decision Making (MA-SDM) and Swarm Robotics (SR). MA-SDM builds upon well-known decision-theoretic models (e.g., Markov decision processes and games) and related algorithms, that come with strong theoretical guarantees. However, the expressiveness of MA-SDM models has limited scalability in face of realistic multi-robot systems [13], resulting in computational overload. In contrast, SR methods which rely on local rules – generally bio-inspired – and relating to Self-Organized Systems [14] can scale up to multiple robots and to highly dynamic environments, but with poor theoretical guarantees [50]. SR approaches are also not geared to express complex realistic tasks or point-to-point communication between robots. In Chroma, **we aim at exploiting the theoretical properties of MA-SDM and the scalability of SR as a means of developing large-scale, communicating and efficient multi-robot systems**. To achieve this goal, we propose to investigate two complementary methodologies.

- First, we plan to investigate incremental expansion mechanisms in anytime decision-theoretic planning, starting from local rules (from SR) to complex strategies with performance guarantees (from MA-SDM) [13]. This methodology is grounded into our research on anytime algorithms, that are guaranteed to stop at anytime while still providing a reliable solution to the original problem. It further relies on decision theoretical models and tools including: Decentralized and Partially Observable Markov Decision Processes and Games, Dynamic Programming, Distributed Reinforcement Learning and Statistical Machine Learning.
- Second, we plan to extend the SR approach by considering the integration of optimization techniques at the local level, i.e. in robot-interaction rules. The purpose is to force the system to explore solutions around the current stabilized state – potentially a local optimum – of the system. We aim at keeping scalability and self-organization properties by not compromising the decentralized nature of such systems. Introducing optimization in this way requires to measure locally the performances, which is generally possible from local perception of robots. The main optimization techniques we will consider are Local Search (Gradient Descent), Distributed Stochastic Algorithm and Reinforcement Learning. See [54] as an illustration of such an approach in a network of intersections where the traffic of autonomous vehicles is optimized.

Beyond this general challenge, Chroma aims at developing algorithms and softwares allowing to deploy, program and test multi-robot systems, including multi-vehicle systems.

[11] e.g. Brian D. Ziebart, N. Ratliff, G. Galagher, C. Mertz, K. Peterson, J. A. Bagnell, M. Hebert, A. K. Dey and S. Srinivasa. *Planning-based Prediction for Pedestrians*. International conference on Intelligent Robots and Systems, 2009.

[12] Steven M. LaValle, Planning Algorithms, Cambridge University Press, 2006.

[13] Martin L. Puterman, Markov Decision Processes; Stuart Russell and Peter Norvig, Artificial Intelligence - A Modern Approach

[14] D. Floreano and C. Mattiussi, Bio-Inspired Artificial Intelligence - Theories, Methods, and Technologies, MIT Press, 2008.

# 4. Application Domains

## 4.1. Future cars and transportation systems

Thanks to the introduction of new sensor and ICT technologies in cars and in mass transportation systems, and also to the pressure of economical and security requirements of our modern society, this application domain is quickly changing. Various technologies are currently developed by both research and industrial laboratories. These technologies are progressively arriving at maturity, as it is witnessed by the results of large scale experiments and challenges such as the Google's car project and several future products announcements made by the car industry. Moreover, the legal issue starts to be addressed in USA (see for instance the recent laws in Nevada and in California authorizing autonomous vehicles on roads) and in several other countries (including France).

In this context, we are interested in the development of ADAS [15] systems aimed at improving comfort and safety of the cars users (e.g., ACC, emergency braking, danger warnings), and of Fully Autonomous Driving functions for controlling the displacements of private or public vehicles in some particular driving situations and/or in some equipped areas (e.g., automated car parks or captive fleets in downtown centers or private sites).

Over the last 8 years we have collaborated with Toyota and with Renault-Nissan on these applications (bilateral contracts, PhD Theses, shared patents). We are also strongly involved (since 3 years) in the innovation project Perfect of the IRT Nanoelec (transportation domain). Recently, we have been awarded an important European ECSEL project [16] involving major European automotive constructors and car suppliers. In this project, Chroma is focusing on the embedded perception component (models and algorithms, including the certification issue), in collaboration with Renault, Valeo and Thales and also with the Inria exploratory team ESTASYS (Rennes). Chroma is also involved in the new ANR project "Valet" (2015-2018) coordinated by the Inria Team RITS (Rocquencourt), dealing with automatic redistribution of car-sharing vehicles and parking valet; Chroma is involved in the pedestrian-vehicle interaction for a safe navigation.

In this context, Chroma has two experimental vehicles equipped with various sensors (a Toyota Lexus and a Renault Zoe, which are maintained by the SED and that allow the team to perform experiments in realistic traffic conditions (Urban, road and highway environments).

## 4.2. Services, intervention, and human assistance robotics

Service robotics is an application domain currently rapidly emerging, and more and more industrial companies (e.g., IS-Robotics, Samsung, LG) are now commercializing service and intervention robotics products such as vacuum cleaner robots, drones for civil or military applications, and entertainment robots. One of the main challenges is to propose robots which are sufficiently robust and autonomous, easily usable by non-specialists, and marked at a reasonable cost. We are involved in developing observation and surveillance systems, by using ground robots (Turtlebot2 robots) or aerial ones (ANR VIMAD [17]).

A more recent challenge for the coming decade is to develop robotized systems for assisting elderly and/or disabled people. In the continuity of our work in the IPL PAL [18], we aim to propose smart technologies to assist electric wheelchair users in their displacements. We address the problem of assisting the user for joining a group of people and navigating in crowded environments, in cooperation with Inria Lagadic team.

Another emerging application to assist people is telepresence robot. We are involved in a project aiming to improve the driving by providing a social and autonomous navigation to the robot, in cooperation with Awabot and Hoomano startups.

[15] Advanced Driver Assistance Systems
[16] ENABLE-S3: European Initiative to Enable Validation for Highly Automated Safe and Secure Systems.
[17] Navigation autonome des drones aériens avec la fusion des données visuelles et inertielles, lead by A. Martinelli, Chroma.
[18] Personnaly assisted Living

We are also investigating service robotics in outdoor environment. In particular, since two years, we work with the ToutiTerre startup to develop navigation models and sensors to allow agricultural pick-up to be autonomously moved in rows of a field.

# 5. Highlights of the Year

## 5.1. Highlights of the Year

### *5.1.1. Evolution of team*

1. Creation of the team : March 2015.
2. Anne Spalanzani, Associate Professor at UPMF, joined the team on December 2015 (previously in Prima team).
3. Leaving of Dizan Vasquez, SRP Inria, for the Apple compagny, on January 2016.

### *5.1.2. Projects and results*

1. Acceptation of the European H2020 Ecsel project "ENABLE" (European Initiative to Enable Validation for Highly Automated Safe and Secure Systems) (November 2015). Chroma is involved in the automated vehicles theme. Fundings for Chroma are 700K€, over 3 years.

# 6. New Software and Platforms

## 6.1. CUDA-HSBOF

- Participants: Lukas Rummelhard, Christian Laugier and Amaury Nègre
- Contact: Amaury Nègre

## 6.2. DATMO (Detection and Tracking of Moving Objects)

- Authors: Trong Tuan Vu and Christian Laugier
- Contact: Christian Laugier

## 6.3. E.R.C.I.

Estimation du risque de collision aux intersections

- Participants: Stéphanie Lefevre, Christian Laugier and Javier Ibanez-Guzman
- Contact: Christian Laugier

## 6.4. Embedded Perception

FUNCTIONAL DESCRIPTION

The method for computing occupancy grids from a stereoscopic sensor, developped in the e-motion team, has been implemented on GPU, using NVIDIA CUDA. This allows a real time implementation and an online processing within the Lexus experimental platform.

- Participants: Amaury Nègre, Christian Laugier and Mathias Perrollaz
- Contact: Christian Laugier

## 6.5. GPU BOF

Bayesian Occupancy Filter on GPU

- Participants: Yong Mao, Christian Laugier, Amaury Nègre and Mathias Perrollaz
- Contact: Christian Laugier

## 6.6. GPU Stro Occupancy Grid

GPU Stereo Occupancy Grid

- Participants: Amaury Nègre and Mathias Perrollaz
- Contact: Christian Laugier

## 6.7. VI-SFM

FUNCTIONAL DESCRIPTION

Experimentary the closed Form Solution for usual-initial data fusion agains real and simulated fusion

- Authors: Jacques Kaiser and Agostino Martinelli
- Contact: Agostino Martinelli

## 6.8. kinetics

- Contact: Jilles Dibangoye

# 7. New Results

## 7.1. Sensor Fusion

### *7.1.1. Observability properties of the visual-inertial structure*

**Participant:** Agostino Martinelli.

We continued to investigate the visual-inertial structure from motion problem by further addressing the following issues:

1. analytically deriving its observability properties in challenging scenarios (i.e., when some of the system inputs are unknown and act as disturbances);
2. obtaining simple and efficient methods for data matching and localization.

Regarding the first issue, we extended our previous results (published last year on the journal Foundations and Trends in Robotics [43]) by also including the extreme case of a single point feature and when the camera is not extrinsically calibrated. Even if this extension seems to be simple, the analytic computation must be totally changed. Indeed, by including in the state the camera extrinsic parameters, the computation, as carried out in [43] in the case when the camera is calibrated, becomes prohibitive.

The problem of deriving the observability properties of the visual-inertial structure from motion problem, when the number of inertial sensors is reduced, corresponds to solve a problem that in control theory is known as the Unknown Input Observability (UIO). This problem is still unsolved in the nonlinear case. In [43] we introduced a new method able to provide sufficient conditions for the state observability. On the other hand, this method is based on a state augmentation. Specifically, the new extended state includes the original state together with the unknown inputs and their time-derivatives up to a given order. Then, the method introduced in [43] is based on the computation of a codistribution defined in the augmented space. This makes the computation necessary to derive the observability properties dependent on the dimension of the augmented state and consequently prohibitive in our case. Our effort to deal with this fundamental issue, was devoted to separate the information on the original state from the information on its extension. We fully solved this problem in the case of a single unknown input. For the general case, we partially solved this problem and we suggested a technique able to partially perform this separation. Since these results are very general (their validity is not limited to the visual-inertial structure from motion problem) we presented them at two international conferences on automatic control (SIAM on Control and Applications, [18] and MED, [16]). By applying these new methods to the the visual-inertial structure from motion problem, we obtained the following result. Even in the case of a single point feature, the information provided by a sensor suit composed by a monocular camera and two inertial sensors (along two independent axes and where at least one is an accelerometer) is the same as in the case of a complete inertial measurement unit (i.e., when the inertial sensors consist of three orthogonal accelerometers and three orthogonal gyroscopes). This result has been presented at ICRA, [17].

Regarding the second issue, our focus was in the framework of Micro Aerial Vehicle navigation. State of the art approaches for visual-inertial sensor fusion use filter-based or optimization-based algorithms. Due to the nonlinearity of the system, a poor initialization can have a dramatic impact on the performance of these estimation methods. Last year, we published, on the journal of computer vision, a closed-form solution providing such an initialization [42]. This solution determines the velocity (angular and linear) of a monocular camera in metric units by only using inertial measurements and image features acquired during a short time interval. This year, we study the impact of noisy sensors on the performance of this closed-form solution. Additionally, starting from this solution, we proposed new methods for both localization and data matching in the context of micro aerial navigation. These methods have been tested in collaboration with the vision and perception team in Zurich (in the framework of the ANR-VIMAD) and published on the journal of Robotics and Autonomous Systems [4].

### 7.1.2. Sensing floor for Human & objects localisation and tracking

**Participants:** Mihai Andries (inria Nancy, Larsen), Olivier Simonin, François Charpillet (inria Nancy, Larsen).

In the context of the PhD of Mihai Andries, co-advised by François Charpillet (Inria Nancy, Larsen) and Olivier Simonin, we investigated a large distributed sensor — a grid of connected sensing tiles on the floor — that was developped by the Maia team, at Nancy, in 2012.

Localization, tracking, and recognition of objects, robots and humans are basic tasks that are of high value in the applications of ambient intelligence. Sensing floors were introduced to address these tasks in a non-intrusive way. To recognize the humans moving on the floor, they are usually first localized, and then a set of gait features are extracted (stride length, cadence, and pressure profile over a footstep). However, recognition generally fails when several people stand or walk together, preventing successful tracking. In the Phd, defended on December 15 [27], we proposed a detection, tracking, and recognition technique which uses objects' weight. It continues working even when tracking individual persons becomes impossible. Inspired by computer vision, this technique processes the floor pressure-image by segmenting the blobs containing objects, tracking them, and recognizing their contents through a mix of inference and combinatorial search. The result lists the probabilities of assignments of known objects to observed blobs. The concept was successfully evaluated in daily life activity scenarii, involving multi-object tracking and recognition on low-resolution sensors, crossing of user trajectories, and weight ambiguity. This model can be used to provide a probabilistic input for multi-modal object tracking and recognition systems. The model and the experimental results have been published in Journal IEEE Sensors [1] and international conference ICRA 2015 [7].

## 7.2. Bayesian Perception

**Participants:** Christian Laugier, Lukas Rummelhard, Amaury Nègre, Jean-Alix David, Procópio Silveira-Stein, Jerome Lussereau, Tiana Rakotovao, Nicolas Turro (sed), Jean-François Cuniberto (sed), Diego Puschini (cea Dacle), Julien Mottin (cea Dacle).

### *7.2.1. Conditional Monte Carlo Dense Occupancy Tracker (CMCDOT)*

**Participants:** Lukas Rummelhard, Amaury Nègre, Christian Laugier.

In 2015, the research work on *Bayesian Perception* has been done as a continuation and an extension of some previous research results obtained in the scope of the former Inria team-project e-Motion. This work exploits the *Bayesian Occupancy Filter (BOF)* paradigm [28], developed and patented by the team several years ago [19]. It also extends the more recent concept of *Hybrid Sampling BOF(HSBOF)* [46], whose purpose was to adapt the concept to highly dynamic scenes and to analyse the scene through a static-dynamic duality. In this new approach, the static part is represented using an occupancy grid structure, and the dynamic part (motion field) is modeled using moving particles. The *HSBOF* software has been implemented and tested on our experimental platforms (equipped Toyota Lexus and Renault Zoe) in 2014 and 2015; it has also been implemented in 2015 on the experimental autonomous car of Toyota Motor Europe in Brussels.

The objective of the research work performed in 2015 was to overcome some of the shortcomings of the *HSBOF* approach [20] , and to obtain a better understanding of the observed dynamic scenes through the introduction an additional object level into the model. The new framework, whose development will be continued in 2016, is called *Conditional Monte Carlo Dense Occupancy Tracker (CMCDOT)* [10]. This work has mainly been performed in the scope of the project *Perfect* of IRT Nanoelec [21] (financially supported by the French ANR agency [22]), and also used in the scope of our long-term collaboration with Toyota.

The *CMCDOT* approach introduces an drastic change in the underlying formal expressions: instead of directly filtering the occupancy data, we have added *hidden states* for representing what is currently present in a cell. Then, the occupancy distribution can then be inferred from those hidden states. Besides presenting a clear distinction between static and dynamic parts, the main interest of this new approach is to introduce a specific processing of dataless areas, excluding them from the velocity estimation (and consequently optimizing the processing of the dynamic parts) and disabling their temporal persistence (which is used to generate estimation bias in newly discovered areas). This updated formalism also enables the introduction of an appropriate formal model for the particle initialization and management (which was previously more isolated).

Another important added feature is the automatic segmentation of the dynamic parts of the occupancy grid, according to its shapes and dynamics. While the *CMCDOT* tracks spatial occupancy in the scene without object segmentation, Detection and Tracking of Moving Objects (DATMO) is often required for high level processing. A standard approach would be to analyse the *CMCDOT* outputs, to apply a clustering algorithm on the occupancy grid (enhanced by velocities), and to use those clusters as potential object level targets. This clustering can turn out to be computationally expensive, considering the grid dimensions and the size and complexity of the dynamic particle model. The basic idea of our new approach is to exploit the particle propagation process within the *CMCDOT*: the way particles are resampled can leads to the wanted segmentation after a number of time steps. After initialization, at each step, the particles that correctly fit the motion of a dynamic object are multiplied, those which do not are forgotten. In a few steps, the best particles propagate in the object, and the object motion is fully described by a set of particles deriving from a common particle root. By marking each particle at the initialization step with a unique identification number,

[19] The *Bayesian programming formalism* developed in e-Motion, pioneered (together with the contemporary work of Thrun, Burgards and Fox [53]) a systematic effort to formalize robotics problems under Probability theory –an approach that is now pervasive in Robotics.

[20] In the current implementation of the HSBOF algorithm, many particles are still allocated to irrelevant areas, since no specific representation models are associated to dataless areas. Moreover, if the filtered low level representation can directly be used for various applications (for example mapping process, short-term collision risk assessment [31], [48], etc), the retrospective object level analysis by dynamic grid segmentation can be computationally expensive and subjected to some data association errors.

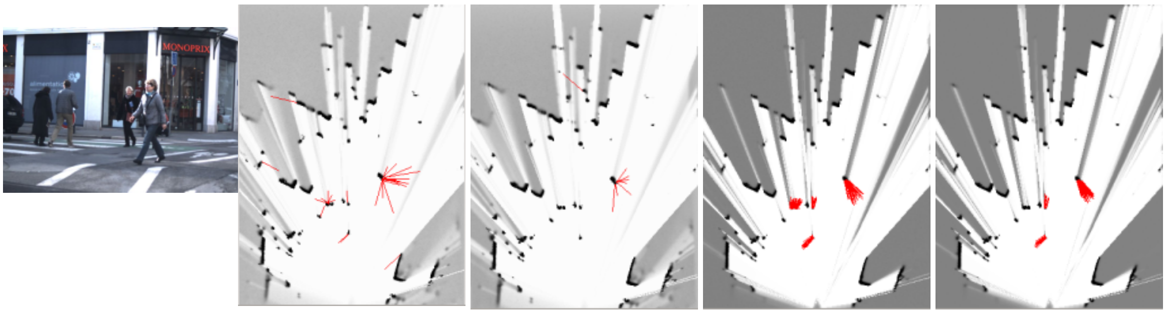
[21] Nanoelec Technological Research Institute (Institut de Recherche Technologique Nanoelec)

[22] National Research Agency (Agence Nationale de la recherche)

all the dynamic areas which are coherent in term of space and motion are marked after few iterations. The convergence of those markers is fastened by additional rules.

| Sequence | Grid size (m) | HSBOF | CMCDOT |
|---|---|---|---|
| Highway | 20x70 | 76.9% | 23.5% |
| Semi-Urban | 30x60 | 89.3% | 46.7% |
| City Center | 30x60 | 93.2% | 40.1% |

*Figure 2. Estimation of irrelevant particle allocation ratio.*



(a) (b) (c) (d) (e)

*Figure 3. Results of the HSBOF with 262144 and 32768 particles (b) and (c), and of the CMCDOT with the same number of particles (d) and (e). Red segments represent the average estimated per-cell velocity. They show that the CMCDOT is more accurate and still manages to track most of the moving pedestrians (even with a severely reduced number of samples), whereas the HSBOF loses track of almost all objects.*

Experimental results showed that the insertion of an "unknown" state in the model leads to a better distribution of dynamic samples on observed areas (see figure 2) and also allows us to be more reactive and accurate on the velocity distributions, while requiring less computing power (see figure 3).

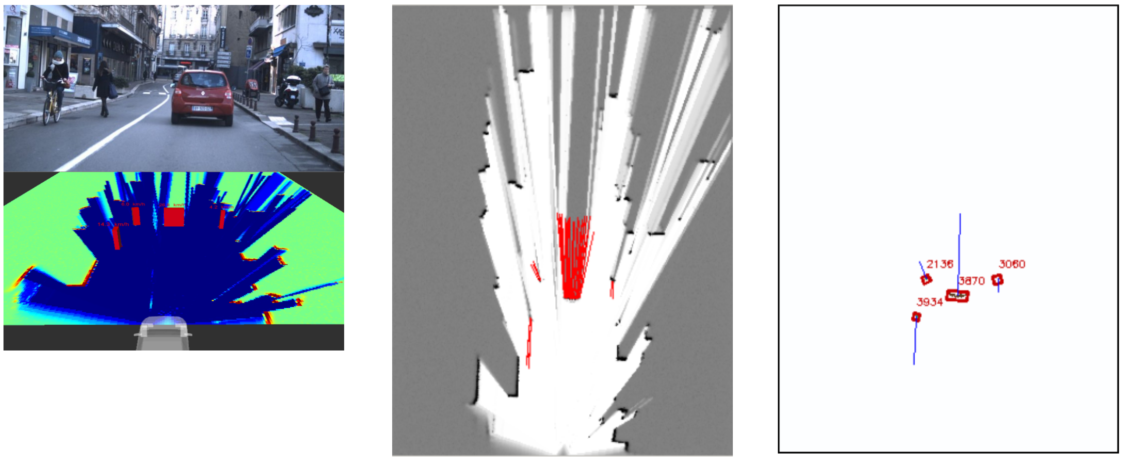
The intrinsic clustering approach has also been tested on real road data, showing promising results in real-time tracking of moving objects, regardless of their type. The method could be improved by managing split-and-merge events that can occur in complex urban environment (see figure 4).

### 7.2.2. *Multimodal dynamic objects classification*

**Participants:** Amaury Nègre, Jean-Alix David.

The method described in section 7.2.1 allows to obtain a list of dynamic objects and to track each object over time. In order to increase the level of representation of the environment, we have developed a method to classify detected objects using both the camera images and the occupancy grid representation estimated by the *CMCDOT*. For each detected object, the bounding box of the object is projected in the camera image and a local image is extracted from the camera. Jointly, we can extract a patch from the occupancy grid around the dynamic object position. The extracted camera image and the occupancy grid patch can then be used as the input of a Deep Neural Network (DNN) to identify the class of the object. The DNN we designed is a combination on two classic neural networks, the "ImageNet" Convolutional Neural Networks [35] for the camera image input and the "LeNet" [37] for the occupancy grid input (see fig 5).

To train and evaluate the model, a dataset has been created from the data recorded with the Lexus platform. We extracted the camera images and the occupancy grid for each object detected by the *CMCDOT* module, then we manually annotated the object class among "pedestrian", "crowd", "car", "truck", "two-wheelers" and




(a)(b) (c) (d)

*Figure 4. Result of the dynamic objects clustering. (a) Camera image; (b) 3D view of the grid with detected objects; (c) resulting occupancy grid with velocity; (d) extracted dynamic objects (red boxes) with velocity (blue segments) and id.*

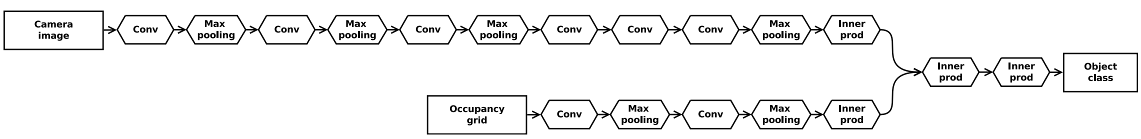



*Figure 5. Deep neural network used for obstacle detection.*

"misc" categories. The resulting dataset contains more than 100000 camera images & occupancy grid pairs. The training process and the classification module has been done by using the open source library caffe [33]. An example of the obtained results is shown on fig 6. The percentage of good classification is greater than 90% on our evaluation dataset.

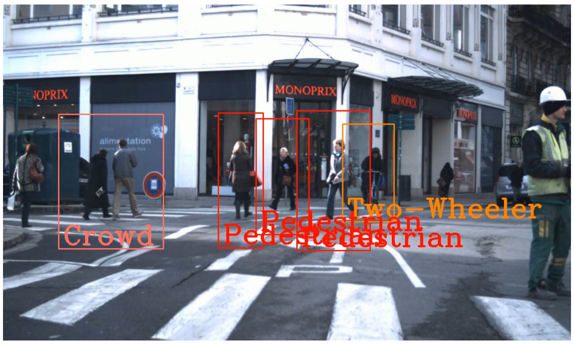



*Figure 6. Result of the dynamic obstacle classification.*

### *7.2.3. Visual Map-Based Localisation with OSM*

**Participants:** Jean-Alix David, Amaury Nègre.

This module aims to improve both the global localization provided by the GPS [23] and the lane-relative localization information estimated by a lane tracker by combining their mutual strengths. The idea is to detect lane markings on the road using a camera, and then to compare the extracted lines with those stored in the map. This is done using the ICP [24] algorithm. This work is described in a confidential Toyota project report entitled *Real Traffic Data Acquisition and Risk Assessment Experiments*.

*7.2.3.1. The map*

Our solution is based on a post-processed OSM [25] map shown on figure 7. Typically, these maps contain information on the roads and lanes, but contain no information about lane markers on the ground. Thus, we ran a semi-manual process to complete the existing maps with information about the number and type of markers.

New data are stocked in a local server. Requests can be sent to this server to fetch map data using HTTP protocol.

*7.2.3.2. Line detection*

The line extraction is done using ridge detection on a top-down view of the camera image. Only one monocular camera is used, as it is an inexpensive sensor, and needs only to be calibrated once. The line detection is based on an algorithm using Laplacian to extract ridges of the monochrome image. The algorithm is implemented for parallelized calculation using CUDA on a GPU, for an improved performance. Figure 8 shows the results of the ridge detector.

[23] Global Positioning System
[24] Iterative Closest Point
[25] OpenStreetMap

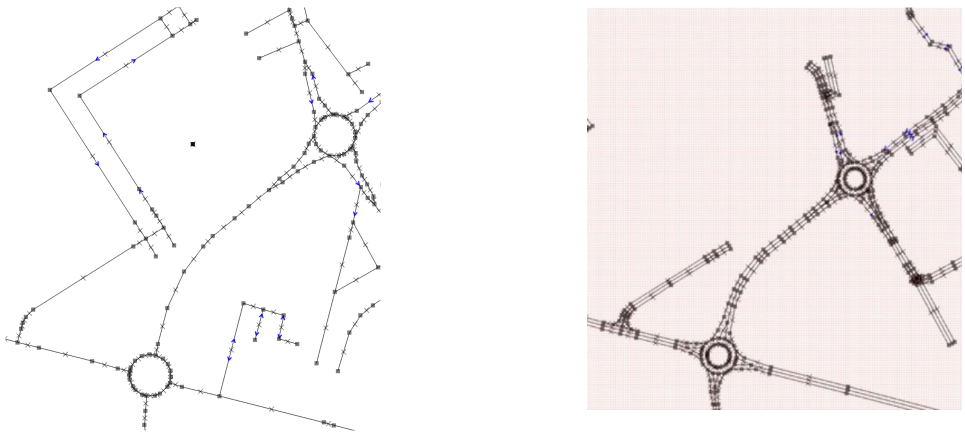


*Figure 7. Data conversion. (a) Raw OSM data, a line represents a road and it is not possible to see the lanes. (b) Modified OSM data, with lane markings.*

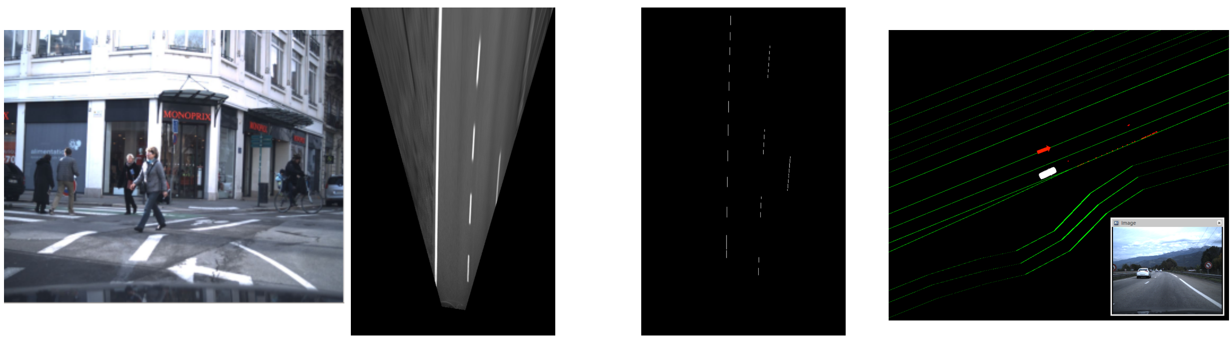



*Figure 8. Ridges detection: (a) Input image (b) Projected image (c) Detected ridges. ICP correction on highway (d)*

#### 7.2.3.3. ICP-based line matching

The extracted lines are matched and aligned with the map using the ICP algorithm to improve the localization of the vehicle. The ICP algorithm iteratively minimizes the total alignment error between the points detected as ridges and the segments of line extracted from the map. Finally, figure 8.d shows how the algorithm can correct the vehicle localization. The algorithm is able to accurately track the orientation and position. However, the lateral displacement may be off by a multiple of the lane width, depending on how the algorithm has been initialized. In practice, this effect is often mitigated due to the existence of single-lane roads such as highway entrances.

The results are very promising on highways, but the algorithm has a lower performance on other types of roads, mostly due to irregularities.

### 7.2.4. Integration of Bayesian Perception System on Embedded Platforms

**Participants:** Tiana Rakotovao, Christian Laugier, Diego Puschini(cea Dacle), Julien Mottin(cea Dacle).

Safe autonomous vehicles will emerge when comprehensive perception systems will be successfully integrated into vehicles. However, our Bayesian Perception approach requires high computational loads that are not supported by the embedded architectures currently used in standard automotive ECUs.

To address this issue, we first explored new embedded hardware architecture credible for the integration of OGs [26] into autonomous vehicles [19]. We studied in particular recent emerging many-core architectures, which offer higher computing performance while drastically reducing the required power consumption (typically less than 1W). In such architectures, the computation of OGs can be divided into several independent tasks, executed simultaneously on separated processing core of a many-core.

Experiments were conducted on data collected from urban traffic scenario, produced by 8 LIDAR layers mounted on the Inria-Toyota experimental Lexus vehicle. These experiments demonstrate that the many-core produces OGs largely in real-time: 6 time faster than the sensor reading rate.

Besides, we also proposed a mathematical improvement of the OG model, for performing multi-sensor fusion more efficiently than the standard approach presented in [29]. In our approach, the fusion of occupancy probabilities requires fewer operations. This model improvement makes it possible the implementation of OG-based multi-sensor fusion on simple hardware architectures. This perspective applies to microcontroller, ASICs or FPGAs which are more and more present in computing platforms recently present on the automotive market.

### 7.2.5. Experimental Vehicle Renault ZOE

**Participants:** Nicolas Turro (sed), Jean-François Cuniberto (sed), Procópio Silveira-Stein, Amaury Nègre, Lukas Rummelhard, Jean-Alix David, Christian Laugier.

#### 7.2.5.1. Experimental Vehicle Renault ZOE

In the scope of the *Perfect* projet of the IRT nanoelec, we have started to develop in 2014, an experimental platform based on an equipped Renault Zoe. The development of this platform has been pursed in 2015.

The vehicle has been enhanced with a tablet to display the new HMI [27], figure 9(a) illustrates. The HMI displays the detected dynamic objects over the camera image and the graph of collision risk at different time horizon.

New experiments have also been designed to test the perception algorithms and the recent implementation of the collision risk alert. These experiments simulate collisions with people using a fabric mannequin, as shown on figure 9(b), and an inflatable ball.

[26] Occupancy Grids
[27] Human Machine Interface

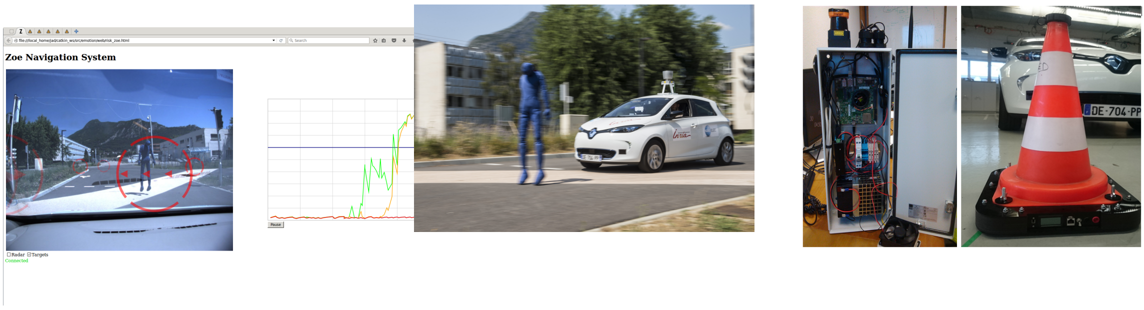



*Figure 9. (a) Display of the HMI (b) Collision simulation with a mannequin (c) On left: picture of the smartbox, on right: picture of the cone.*

Finally, we have also developed two movable devices in order to enhance V2X [28] communication experiments (see figure 9(c)):

1. A movable communicating cone equipped with a GPS and a V2X communication box, which broadcast its position to near V2X listeners.
2. A movable smartbox equipped with a GPS, a V2X communication box, a LIDAR sensor and a Nvidia Tegra K1 board. The *CMCDOT* algorithm is implemented on it, and the detected objects are broadcasted to other communicating devices. The smartbox can be mounted on another vehicle or be placed as part of a static infrastructure. Both are alimented by batteries and aim at minimizing their energy consumption.

## 7.3. Situation Awareness

**Participants:** Christian Laugier, Alejandro Dizan Vasquez Govea, Procópio Silveira-Stein, David Sierra-Gonzalez, Mathieu Barbier, Stephanie Lefevre(uc Berkeley).

### *7.3.1. Framework for Motion Prediction and Collision Risk Assessment*

**Participants:** Christian Laugier, Alejandro Dizan Vasquez Govea, Procópio Silveira-Stein, Stephanie Lefevre(uc Berkeley).

For several years, the challenging scientific problem of Motion Prediction, Risk Assessment and Decision-Making in open and dynamic environments has been one of our main research topics (see activity reports of the former e-Motion Inria team-project). Throughout 2016, we have continued this line of work by developing several new frameworks for Motion Prediction and Collision Risk Assessment in complex dynamic scenes involving multiple moving agents having various behaviors.

A first contribution has been the extensive experimental validation in real conditions –together with the University of Berkeley– of our *Intention-Expectation* approach: a high-level approach to risk assessment which avoids the complexity of trajectory-level reasoning while being able to take multi-vehicle interactions into account [9]. These results have also been integrated into a Mooc course at the graduate and undergraduate levels [25]. They have also been presented in several invited talks [24] [21] [22] [23].

Another contribution relies in the implementation of some the proposed models on two experimental vehicles (Lexus and Zoé experimental platforms). As mentioned in section 7.2.5, several experiments on short-term collision risk assessement have been successfuly conducted with these platforms (c.f. [10], [15]). This work will be continued in 2016, in the scope of our ongoing collaborative projects with Toyota, Renault and IRT nanoelec.

[28] Vehicle-to-Vehicle and Vehicle-to-Infrastructure

### *7.3.2. Planning-based motion prediction for collision risk estimation in autonomous driving scenarios*

**Participants:** David Sierra-Gonzalez, Alejandro Dizan Vasquez Govea, Christian Laugier.

The objective is to develop a collision risk estimation system capable of reliably finding the risk of collision associated to the different feasible trajectories of the ego-vehicle. This research work is done in the scope of the Inria-Toyota long-term cooperation and of the PhD thesis work of David Sierra- Gonzales.

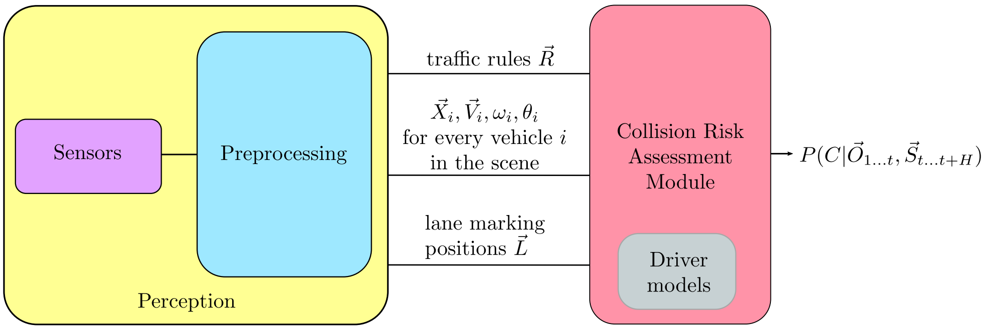



*Figure 10. Black box model for the Collision Risk Assessment Module. The number of inputs expected from the perception module is not comprehensive at this point.*

Figure 10 shows the black box model of the system. At a given timestep, the system takes the following inputs: the traffic rules in effect; the position, velocity, angular velocity and heading of each vehicle $i$ in the scene; and the position of the lane markings. Thus, at each timestep $t$ we construct an observation vector $1\overrightarrow{O}_t = \left(\overrightarrow{R}_t, \{\overrightarrow{X}_i, \overrightarrow{V}_i, \omega_i, \theta_i\}_t, \overrightarrow{L}_t\right)$ with all the high-level perception inputs, and a state vector $\overrightarrow{S_t}$ with only the minimum variables necessary to describe the scene. The proposed system aims to calculate the probability of collision $C$ of the ego-vehicle for a sequence of future states up until a fixed time horizon $H$. That can be expressed as $P(C|\overrightarrow{O}_{1\cdots t}, \overrightarrow{S}_{t\cdots t+H})$. This information can then be used by a path-planner to decide upon the safest trajectory.

One key factor for the correct estimation of collision risk is the ability to predict the motion of the dynamic obstacles in the scene, that is, the other drivers. We opt here for a planning-based approach, which assumes that drivers instinctively act as to maximize a reward (or equivalently, minimize a cost). This reward function encodes the preferences of the driver to, for instance, keep a minimum distance with the vehicle in front, drive in the right lane in the highway, or respect the speed limits. Given such a reward function, Markov Decision Processes (MDP) constitute an adequate framework for the motion prediction problem. Moreover, by using Inverse Reinforcement Learning (IRL) algorithms, we can obtain such reward function directly from expert demonstrations (i.e. simply observing how people drive).

At this point, two well-known IRL algorithms ( [26], [58]) have been implemented and used to obtain a generic driver model from human demonstrations performed on a highway simulator. This driver model can now be used to predict the future behavior of the dynamic obstacles in the scene.

## 7.4. Motion-planning in human-populated environment

### *7.4.1. Planning-based motion prediction for pedestrians in crowded environments*

**Participant:** Alejandro Dizan Vasquez Govea.

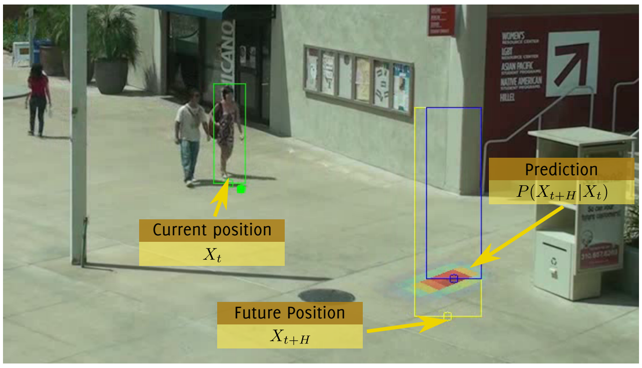



*Figure 11. Example of spatiotemporal state prediction for a single agent, indicating its current and future position after 8 sec (green and yellow boxes) as well as the predicted position probability and its maximum value (blue box)*

We have also explored the application of motion planning algorithms to the prediction of human motion (Fig. 11). We have proposed a novel planning-based motion prediction approach [12] which addresses the weaknesses of the previous state-of-the-art motion prediction technique [34], namely:

1. *High computational complexity*. This is dealt with by using the Fast Marching Method (FMM) [49] an efficient deterministic planning algorithm which computes the cost-to-go to a given location for every cell of a grid representing the agent's workspace. This grid is then used in a novel goal prediction algorithm and to produce a path-like prediction equivalent to the output of the Markov Decision Processes (MDPs) used by Kitani.
2. *Limited ability to model the temporal evolution along the predicted path*: this is addressed through the use of a velocity-dependent probabilistic motion model which is used to estimate a probability distribution of the future agent's position. This is then fused with a novel cost-based model to produce a full spatiotemporal prediction.
3. *Constant-goal assumption*. We propose a gradient-based goal prediction approach which does not rely on filtering, making it capable of quickly recognizing intended destination changes as they happen.

In our preliminary experiments, the proposed method significantly outperforms the accuracy of Kitani's approach while reducing the computation time by a factor of 30 using a parallel version of our algorithm.

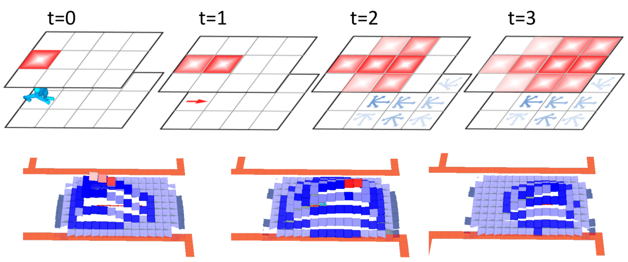



*Figure 12. Illustration of (a) the flow-grid model (b) the pheromone model of human motion prediction.*

### 7.4.2. Modeling human-flows from robot(s) perception

**Participants:** Olivier Simonin, Jacques Saraydaryan, Fabrice Jumel.

To deal with navigation in highly populated environments, eg. flows of humans, we started to investigate the problem of mapping these flows. The challenge is to build such an information from robots perception while they move autonomously to perform their tasks. We also work on predicting humans location from the perceptions and the constructed flow-grid. This led us to define two models : i) a flow-grid mapping computing in each cell the probability to move in each of the $k$ possible directions (illustrated in figure 12.a), ii) a pheromone-based model allowing to compute the current possible location of humans (flows), see figure 12.b. We are currently measuring the efficiency of the proposed mapping compared to existing models (which do not model directions). First results will be submitted soon (to IROS 2016).

## 7.5. Multi-robot Motion-planning in dynamic environments

### 7.5.1. Benchmarking and extension of multi-robot strategies

#### 7.5.1.1. Exploration of unknown and populated environments

**Participants:** Olivier Simonin, Nassim Kaldé (phd. Student, Larsen Inria Nancy), François Charpillet (inria Larsen, Nancy), Jan Faigl (ctu, Czech University Of Prague).

Exploration of unknown environment with a group of mobile robots consists mainly to compute a strategy that allows to visit efficiently the area while considering different constraints. These constraints can be trajectory coordination (between robots), presence of humans and limits on time, communication, and computational ressources allowed to robots. The exploration problem is related with mapping, surveillance (eg. patrolling) problems. In this context, O. Simonin and P. Lucidarme (University of Angers) published a general article on multi-robot mapping in the magazine Techniques de l'Ingénieur [5] (2015).

**Study of frontier-based strategies**

In this context, frontier-based approaches looks for an efficient allocation of the navigational goals which must be situated between the known and unknown areas (the frontiers). Goal candidate locations are repeatedly determined during the exploration. Then, the assignment of the candidates to the robots is solved as the task-allocation problem. A more frequent decision-making may improve performance of the exploration, but in a practical deployment of the exploration strategies, the frequency depends on the computational complexity of the task-allocation algorithm and available computational resources. Therefore, we proposed an evaluation framework to study exploration strategies independently on the available computational resources and we reported a comparison of the selected task-allocation algorithms deployed in multi-robot exploration [30]. This work is supported by the French-Czech PHC "Murotex".

**Exploration in populated environments**

In the context of the Phd of Nassim Kaldé, co-supervized by F. Chapillet (Inria Nancy, Larsen) and O. Simonin (Chroma), we study exploration in populated environments, in which pedestrian flows can severely impact performances. However, humans have adaptive skills for taking advantage of these flows while moving. Therefore, in order to exploit these human abilities, we propose a novel exploration strategy that explicitly allows for human-robot interactions. Our model for exploration in populated environments combines the classical frontier-based strategy with our interactive approach. For this purpose, we proposed an interaction model where robots can locally choose a human guide to follow and define a parametric heuristic to balance interaction and frontier assignments. This model is introduced in publication [3], where we evaluate to which extent human presence impacts the exploration model in terms of coverage ratio, travelled distance and elapsed time to completion. A simulator, based on V-REP and illustrated in figure 13.a, has been developped to conduce the experimental measures.

#### 7.5.1.2. Patrolling static and dynamic environments

**Participants:** Olivier Simonin, Jacques Saraydaryan, Fabrice Jumel, Mihai Popescu, Herve Rivano (inria Urbanet).

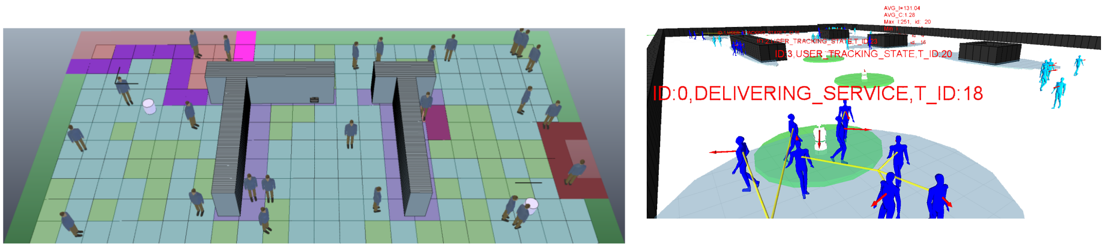



*Figure 13. (a) Simulator to study exploration in populated environment based on V-REP (b) Simulator for dynamic patroling of people based on PedSim.*

**Patrolling moving people**

In the context of service robotics, we address the problem of serving people by a set of collaborating robots, that is to delever regularly services to moving people. We re-defined this problem as a dynamic patrolling task, that we called the robot-waiters problem, where robots have to regularly visit all the moving persons. In the publication [11], we proposed different criteria and metrics suitable to this problem, by considering not only the time to patrol all the people but also the equity of the delivery. We proposed and compared four algorithms, two are based on standard solutions to the static patrolling problem and two are defined according the specificity of patrolling moving entities. In order to limit robot traveled distances, the last approach introduces a clustering heuristic to identify groups among people. To compare algorithms and to prepare real experiments we developped a simulator combining a pedestrian model (PedSim) and a robotic model, illustrated in figure 13.b. Experimental results show the efficiency of the specific new approaches over standard approaches. We also analysed the influence of the number of robots on the performances, for each approach.

We are currently developping new algorithms using the mapping and prediction of human flows based on the work presented in section 7.4.2.

**Patrolling WSN**

In the multi-robot patrolling context, we investigated the problem of visiting regularly a set of fixed sensors by computing single-cycles on the graph formed by the WSN (Wireless sensors network). We set this problem as a graph covering with bounded hamiltonian cycles (in the M2R internship of Mihai-Ioan Popescu, now continuing as PhD student in Chroma). After giving insights of NP-hardness, we proposed a generic heuristic algorithm for solving the GCBHC. It works in two steps: the first one partitions the vertices, the second one computes hamiltonian cycles on each partition. We adapted the classic Multilevel Subgraph Partitioning algorithm to the specific requirements yielded by the networking metrics. To avoid the high complexity of this algorithm, we proposed another heuristic which exploits the geometric structure of the graph, the North-Eastern Neighbour heuristic. We implemented two classic hamiltonian cycle heuristics, one is based on Minimum Spanning Trees computations and the other on Christofides algorithm. Comparisons on randmly-generated graphs showed that the Christofides algorithm computes shorter cycles. An article presenting this work has been written and will be submitted soon.

### 7.5.2. Anytime algorithms for multi-robot cooperation

#### 7.5.2.1. Observation of complex scenes

**Participants:** Olivier Simonin, Jilles Dibangoye, Laetitia Matignon (liris), Christian Wolf (liris), Jonathan Cohen (internship), Stefan Chitic.

Solving complex tasks with a fleet of robots requires to develop generic strategies that can decide in real time (or time-bounded) efficient and cooperative actions. This is particularly challenging in complex real environments. To this end, we explore anytime algorihms and adaptive/learning techniques.

The INSA BQR project "Crome" [29], led by O. Simonin, motivated the exploration of the joint-observation of complex (dynamic) scenes by a fleet of mobile robots. In our current work, the considered scenes are defined as a sequence of activities, performed by a person in a same place. Then, mobile robots have to cooperate to find a spatial configuration around the scene that maximizes the joint observation of the human pose skeleton. It is assumed that the robots can communicate but have no map of the environment and no external localisation.

To attack the problem, in cooperation with colleagues from vision (C. Wolf, Liris), we proposed an original concentric navigation model allowing to keep easily each robot camera towards the scene (see fig. 14.a). This model is combined with an incremental mapping of the environment in order to limit the complexity of the exploration state space. We have also defined the marginal contribution of each robot observation, to facilitate stability in the search, while the exploration is guided by a meta-heuristics. We developped a simulator (fig. 14.b) that allows to compare the variants of the approach and to show its features such as adaptation to the dynamic of the scene and robustness to the noise in the observations. Preliminary results have been presented in [8].

We have also developped an experimental framework, using Turtlebot2 robots, presented in figure 14.c. Experimental measures and validation are in progress.

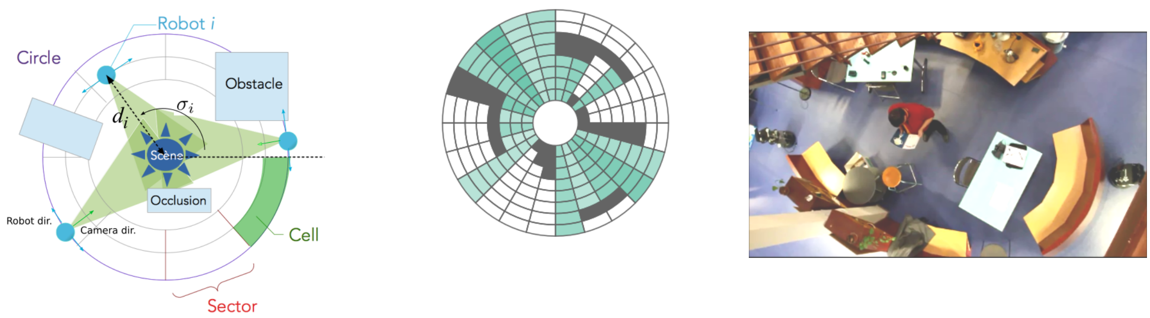



*Figure 14. Illustrations (a) Concentric navigation model, (b) Simulator and (c) experimental setup with Turtlebot 2.*

#### *7.5.2.2. Middleware for multi-robot systems deployment*

**Participants:** Stefan Chitic, Julien Ponge (citi, Dynamid), Olivier Simonin.

Multi-robots systems (MRS) require dedicated tools and models to face the complexity of their design and deployment (there is no or very limited tools/middleware for MRS). In this context, we addressed the problem of neighbors and service discovery in an ad-hoc network formed by a fleet of robots. Robots needs a protocol that is able to constantly discover new robots in their coverage area. This led us to propose a robotic middleware, SDfR, that is able to provide service discovery. This protocol is an extension of the Simple Service Discovery Protocol (SSDP) used in Universal Plug and Play (UPnP) to dynamic networks generated by the mobility of the robots. Even if SDfR is platform independent, we proposed a ROS integration in order to facilitate the usage. We evaluated a series of overhead benchmarking across static and dynamic scenarios. Eventualy, we experimented some use-cases where our proposal was successfully tested with Turtlebot 2 robots. Results have been presented to the national conference CAR'2015 and will appear in the international conference ICAART 2016 (accepted).

[29] Coordination d'une flottille de robots mobiles pour l'analyse multi-vue de scènes complexes

### *7.5.3. Sequential decision-making under uncertainty*

Sequential decision-making under uncertainty is a core area of artificial intelligence, optimization, operations research, machine learning, and robotics. It involves one or multiple decision makers (or agents or robots) reasoning about the course of actions to achieve collective or self-interested goals while accounting both for the outcomes of current decisions and for future decision-making opportunities. Markov models (e.g., Markov decision processes and Markov games) have emerged as normative frameworks for optimizing decision under uncertainty. These models encompass a wide range of real-world applications: controlling intelligent vehicles; optimizing the production and distribution of energy resources; protecting endangered species; making telecommunication protocols faster and safer; monitoring and assisting elderly patients at home; designing robotic exploration technologies for search and rescue; but also many other applications. Decentralized partially observable Markov decision processes have emerged as the fundamental model to address multiple decision makers' decision-theoretic planning and learning problems. In that direction, we investigate generic, highly scalable and adaptable planning and learning algorithms to apply eventually in multi-robot planning tasks.

#### *7.5.3.1. Structural results for cooperative decentralized control problems*

**Participants:** Jilles S. Dibangoye, Olivier Simonin, Olivier Buffet (inria Nancy, Ex Maia Team), Mamoun Idrissi (internship, Insa de Lyon).

The intractability in cooperative, decentralized control problems is mainly due to prohibitive memory requirements in both optimal policies and value functions. The complexity analysis has emerged as the standard method to estimating the memory needed for solving a given computational problem, but complexity results may be somewhat limited. Our work [13] introduces a general methodology, called the structural analysis, for the design of optimality-preserving concise policies and value functions, which will eventually lead to the development of efficient theory and algorithms. For the first time, we showed that memory requirements for policies and value functions may be asymmetric, resulting in cooperative, decentralized control problems with exponential reductions in memory requirements. To apply this theoretical in robotics, we investigate during M. Idrissi's internship the robotic coverage of unknown areas.

#### *7.5.3.2. State-of-the-art algorithms for optimally solving Dec-POMDPs*

**Participants:** Jilles S. Dibangoye, Christopher Amato (univ. New Hampshire), Olivier Buffet (inria Nancy, Ex Maia Team), François Charpillet (inria Nancy, Larsen Team), Martin Pugnet (master Student, U. Claude Bernard Lyon).

Decentralized partially observable Markov decision processes (Dec-POMDPs) provide a general model for decision-making under uncertainty in cooperative decentralized settings but are difficult to solve optimally (NEXP-Complete). As a new way of solving these problems, we introduced the idea of transforming a Dec-POMDP into a continuous-state deterministic MDP with a piecewise-linear and convex value function. This approach makes use of the fact that planning can be accomplished in a centralized offline manner while execution can still be decentralized. This new Dec-POMDP formulation, which we call an occupancy MDP, allows powerful POMDP and continuous-state MDP methods to be used for the first time. To provide scalability, we refine this approach by combining heuristic search and compact representations that exploit the structure present in multi-agent domains, without losing the ability to converge to an optimal solution. In particular, in [14], we introduce a feature-based heuristic search value iteration (FB-HSVI) algorithm that relies on feature-based compact representations, point-based updates, and efficient action selection. However, scalability remains limited when the number of agents or problem variables becomes large. To overcome this limitation, we show that, under certain separability conditions of the optimal value function, the scalability of this approach can increase considerably. This separability is present when there is the locality of interaction between agents, which can be exploited to improve performance. A theoretical analysis demonstrates that FB-HSVI terminates in finite time with an optimal solution. We include an extensive empirical analysis using well-known benchmarks, thereby confirming that our approach provides significant scalability improvements compared to the state of the art. We push even further the envelope, during Martin's internship, assuming we only have access to an incomplete model of the world. This more realistic assumption that would ease application to robotics leads us directly to learning algorithms inspired from FB-HSVI.

*7.5.3.3. Distributed projected gradient-descent algorithm applied to smart grids*

**Participants:** Jilles S. Dibangoye, Arnaud Doniec (uria – Ecole Des Mines de Douai, France), H. Fakham, F. Colas And X. Guillaud (l2ep – Arts Et Métiers Paristech, France).

In a smart grid context, the increasing penetration of embedded generation units leads to a greater complexity in the management of production units. In this work, we focus on the impact of the introduction of decentralized generation for the unit commitment (UC) problem. Unit commitment problems consist in finding the optimal schedules and amounts of power to be generated by a set of generating units in response to an electricity demand forecast. While this problem has received a significant amount of attention, classical approaches assume that these problems are centralized and deterministic. However, these two assumptions are not realistic in a smart grid context. Indeed, finding the optimal schedules and amounts of power to be generated by multiple distributed generator units is not trivial since it requires to deal with distributed computation, privacy, stochastic planning, etc. Our contribution focuses on smart grid scenarios where the main source of complexity comes from the proliferation of distributed generating units. In solving this issue, we consider distributed stochastic unit commitment problems. In [2], we introduce a novel distributed gradient descent algorithm which allows us to circumvent classical assumptions. This algorithm is evaluated through a set of experiments on real-time power grid simulator.

# 8. Bilateral Contracts and Grants with Industry

## 8.1. Bilateral Contracts with Industry

### *8.1.1. Toyota Motors Europe*

[Feb 2006 - Feb 2009] [Dec 2010 - Dec 2015]

The contract with Toyota Motors Europe is a joint collaboration involving Toyota Motors Europe, Inria and ProBayes. It follows a first successful short term collaboration with Toyota in 2005.

This contract aims at developing innovative technologies in the context of automotive safety. The idea is to improve road safety in driving situations by equipping vehicles with the technology to model on the fly the dynamic environment, to sense and identify potentially dangerous traffic participants or road obstacles, and to evaluate the collision risk. The sensing is performed using sensors commonly used in automotive applications such as cameras and lidar.

This collaboration has been extended for 4 years and Toyota provides us with an experimental vehicle Lexus equipped with various sensing and control capabilities. Several additional connected technical contracts have been signed also.

### *8.1.2. Renault*

[Jan 2010 - Feb 2013]

This contract was linked to the PhD Thesis of Stephanie Lefèvre. The objective is to develop technologies for collaborative driving as part of a Driving Assistance Systems for improving car safety. Both vehicle perception and communications are considered in the scope of this study. An additional short-term contract (3 months) has also been signed in november 2012.

### *8.1.3. IRT-Nano Perfect (2012-2014, and 2015-2017)*

Perfect is a project supported by ANR in the scope of the IRT (Technological Research Institute) Nanoelectronic driven by the CEA (Nuclear Energy Agency). The partners of the project are the CEA-LETI LIALP laboratory, ST-Microelectronics and Inria. The goal of this project is to propose integrated solutions for "Embeeded Bayesian Perception for dynamic environments" and to develop integrated open platforms. During the first phase of the project (2012-2014), the focus is on the domain of transportation (both vehicle and infrastructure); health and smart home sectors will also be considered in the second phase (2015-2017).

# 9. Partnerships and Cooperations

## 9.1. Regional Initiatives

### 9.1.1. Projet AAP ARC6 "" (2015-18)

**Participants:** Olivier Simonin, Anne Spalanzani, Fabrice Valois (insa de Lyon, Inria Urbanet).

Regional project (Rhône-Alpes) "Mobilité au sein de flottes de robots sous contrainte de maintien de la connectivité" ARC6, 2015-2018. Leader : O. Simonin.

This project funds the PhD thesis of Mihai-Ioan Popescu, who started on november 2015, and co-advized by O. Simonin, A. Spalanzani and F. Valois. The project involves also the Pole de compétitivité "Via Meca".

## 9.2. National Initiatives

### 9.2.1. ANR

#### 9.2.1.1. ANR "VIMAD" (2015-17)

The VIMAD project aims at developing a robust and reliable perception system, only based on visual and inertial measurements, to enhance the navigation capabilities of fully autonomous micro aerial drones. It also aims at acquiring a deep theoretical comprehension of the problem of fusing visual and inertial measurements, by investigating its observability properties in challenging scenarios.

The activities related to this project, followed the work-plan (first year). They regarded the usage of our closed-form solution (recently published on the journal of computer vision, [42]) in the framework of micro aerial navigation in order to:

1. automatically perform state initialization;
2. improve the data matching process.

Additionally, the activities of VIMAD regarded the investigation of an unsolved problem in control theory, which is the unknown input observability problem in the nonlinear case, and its applications to the visual-inertial structure from motion problem.

See section 7.1.1 for a description of the results obtained during this first year of the project.

#### 9.2.1.2. ANR "Valet" (2016-18)

The ANR VALET project proposes a novel approach for solving car-sharing vehicles redistribution problem using vehicle platoons guided by professional drivers. An optimal routing algorithm is in charge of defining platoons drivers' routes to the parking areas where the followers are parked in a complete automated mode. The consortium is made of 2 academic partners : Inria (RITS, Chroma, Prima) and Ircyyn Ecole Centrale de Nantes and the AKKA company.

In the VALET project we will propose a novel approach for solving car-sharing vehicles redistribution problem using vehicle platoons guided by professional drivers, retrieving vehicles parked randomly on the urban parking network by users. The phD student (Pavan Vashista) recruited in this project will focus on integrating models of human behaviors (pedestrian and/or drivers), proxemics (human management of space) and traffic rules to evaluate and communicate a risk to pedestrians that may encounter the trajectory of the VALET vehicle. His phD thesis will start on february 2016 and will be codirected by D. Vaufreydaz (Inria/PervasiveInteraction).

## 9.3. European Initiatives

### 9.3.1. FP7 & H2020 Projects

#### 9.3.1.1. "ENABLE" Ecsel Project

ENABLE-S3 means "European Initiative to Enable Validation for Highly Automated Safe and Secure Systems". It is a H2020 Ecsel project.

ENABLE-S3 is *industry-driven* and therefore aims to foster the leading role of the European industry. This is also reflected in its *use case driven approach*. The main technical objectives are extracted from the use cases defined by the industrial partners, in order to validate the success of the developed methods and tools.

Recent scientific publications from the automotive domain predict that more than 100 Mio km of road driving is required for the thorough validation of a fully automated vehicle. Only if this extensive test is done, it is statistically proven that the automated vehicle is as safe as a manually driven car. Taking further into account the high number of vehicle variants and software versions, one can easily understand that *new validation approaches* are required to validate new Electronics, Components and Systems (ECS) for automated vehicles within a reasonable time period at reasonable costs. The same characteristic hold for other transportation domains such as aeronautics, maritime or rail.

The ENABLE-S3 project will provide European industry with leading-edge technologies that *support the development of reliable, safe and secure functions for highly automated and/or autonomously operating systems* by enabling the *validation and verification at reduced time and costs*.

Enables-S3 is a large European consortium, involving a French consortium leaded by Valeo, and including Thales, Renault and Inria. The project will start in March-April 2016 and will have a duration of 3 years.

### 9.3.2. Collaborations in European Programs, except FP7 & H2020

Program: PHC (Barande) French-Czech bilateral project

Project acronym: MUROTEX

Project title: Multi-Agent Coordination in Robotic Exploration and Reconnaissance Missions

Duration: Jan. 2014 - Dec. 2015

Coordinator: O. Simonin & J. Faigl (Prague Univ.)

Other partners: CTU (Czech Republic), Inria Larsen team.

Abstract: The main objective of the project is to develop a distributed planning framework for efficient task-allocation planning in exploration and reconnaissance missions by a group of mobile robots operating in an unknown environment with considering communication constraints and uncertainty in localization of the individual team members. One main challenge is to decentralize the decision, in order to scaling up with large fleet of robots (existing solutions are centralized or depend on full communication).

### 9.3.3. Collaborations with Major European Organizations

- Autonomous System laboratory: ETHZ, Zurich (Switzerland)

  Subject: Vision and IMU data Fusion for 3D navigation in GPS denied environment.
- Robotics and Perception Group: University of Zurich (Switzerland)

  Subject: Vision and IMU data Fusion for 3D navigation in GPS denied environment.
- Karlsruhe Institut fur Technologie (KIT, Germany)

  Subject: Autonomous Driving (student exchanges and common project).
- Vislab Parma (Italy)

  Subject: Embedded Perception & Autonomous Driving (visits, projects submissions, and book chapter in the new edition of the Handbook of Robotics).
- Czech Technical University CTU in Prague (Czech Republic)

  Subject: Distributed algoritms for multi-robot cooperation (PHC "Murotex" 2013-15 and renewal).
- Department of Electrical & Computer Engineering: University of Thrace, Xanthi (GREECE)

  Subject: 3D coverage based on Stochastic Optimization algorithms
- Universidade de Aveiro (Portugal)

  Subject: Leader following. co-direction of P. Stein phD.

- Centro De Automatica y Robotica, UPM-CSIC, Madrid (Spain)

  Subject: Target interception.
- Bonn-Rhein-Sieg University of Applied Sciences (Germany)

  Subject: Using Semantic Information for Robot Navigation.
- Social Robotics Laboratory, Freiburg (Germany)

  Subject: Human behavior understanding.
- BlueBotics: BlueBotics Company, Lausanne (Switzerland)

  Subject: Implementation of self-calibration strategies for wheeled robots and SLAM algorithms for industrial purposes.

## 9.4. International Initiatives

### *9.4.1. Inria International Labs*

- iCeiRA [30] international robotics laboratory led by Prof Ren Luo from NTU (Taiwan). Christian Laugier (Inria) and Raja Chatila (UPMC & CNRS) have actively participated to the starting of this laboratory in 2012 and are external Principal Investigators.

  Subject: Human centered robotics.
- SAMPEN

  Title: self adaptive mobile perception and navigation

  International Partner (Institution - Laboratory - Researcher):

  NTU (TAIWAN)

  Duration: 2014 - 2016

  See also: http://emotion.inrialpes.fr/people/spalanzani/HomeSAMPEN.html

  The associate team project is a Robotic project. The aim of the project is to propose a self-adaptive system of perception combined with a system of autonomous navigation. Usually, systems of perception rely on a set of specific sensors and a calibration is done in a specific environment. We propose to develop some methods to make perception systems adaptive to the environmental context and to the set of sensors used. This perception, that can be embedded on the mobile robot as well as on home structures (wall, ceiling, floor), will be helpful to localize agents (people, robot) present in the scene. Moreover, it will give information to better understand social scenes. All information will be used by the navigation system to move with a behavior that fit the context.

#### *9.4.1.1. Informal International Partners*

- UC Berkeley & Stanford University (CA, USA)

  Subject: Autonomous Driving (postdoc in the scope of Inria@SV, common publications and patent).
- Massachussetts Institute of Technology (MIT), Cambridge, MA (USA)

  Subject: Decentralized Control of Markov Decision Processes.

### *9.4.2. Participation In other International Programs*

- IEEE Robotics and Automation. Christian Laugier is member of several IEEE committees, in particular: IROS Steering committee, co-chair of Technical Committee on Autonomous Ground vehicles and Intelligent Transport Systems, Steering committee and Senior Editor of IEEE Transactions on Intelligent Vehicles. Olivier Simonin is member of the TC on Multi-Robot Systems (MRS).

  Subject: International Robotics Research Supporting.

[30] International Center of Excellence in Intelligent Robotics and Automation Research.

# 10. Dissemination

## 10.1. Promoting Scientific Activities

### *10.1.1. Scientific events organisation*

*10.1.1.1. General chair, scientific chair*

- C. Laugier was General Chair (with Ph. Bidaud as co-Chair) of the IEEE ARSO conference "The 2015 IEEE International Workshop on Advanced Robotics and its Social Impacts".
- C. Laugier is a member of the Advisory / Steering Committee of IEEE/RSJ IROS conference.
- C. Laugier was co-organizer of the workshop "7th Workshop on Planning, Perception and Navigation for Inteligent Vehicles", IROS 2015, Hamburg, September 2015 ( 160 attendees).
- O. Simonin was co-organizer of the Workshop DEMUR "On-line decision-making in multi-robot coordination", IROS 2015, Hamburg, October 2015.
- O. Simonin was co-Chair of CAR 2015 "The 10th National Conference Control Architectures of Robots", Lyon, July 2015.

*10.1.1.2. Member of the organizing committees*

- C. Laugier is a member of the Advisory / Steering Committee of IEEE/RSJ IROS conference.
- C. Laugier is a member of the Editorial Board of the JSME Robomech Journal.
- O. Simonin was Local arrangement chair of the IEEE ARSO conference.
- O. Simonin was Chair (with J. Ponge) of the organization committee of CAR 2015.
- O. Simonin and J. Saraydaryan were members of the organization committee of the Colloque Jacques Cartier "Robotique, Services et Santé", 31.10-1.11, 2015.

### *10.1.2. Scientific events selection*

*10.1.2.1. Member of the conference program committees*

- C. Laugier was Associate Editor for the IEEE/RSJ IROS 2015 and 2016 conferences.
- C. Laugier was Associate Editor for the IEEE ICRA 2015 and 2016 conferences.
- Jilles S. Dibangoye was Program Committee member of the following conferences:
  - International Joint Conference on Artificial Intelligence (IJCAI)
  - AAAI Conference on Artificial Intelligence (AAAI)
  - Autonomous Agent and Multi-agent Systems International Conference (AAMAS)
- O. Simonin was Program Committee member for IFAC/ACM ICINCO (International Conference on Informatics in Control, Automation and Robotics)
- O. Simonin is Program Committee member of the JFSMA conference since 2008 (Journées Francophones sur les Systèmes Multi-Agents).

*10.1.2.2. Reviewer*

- A. Martinelli served, in quality of reviewer, at the following international conferences: ICRA 2015, IROS 2015, ICUAS 2015, ACC 2015
- O. Simonin served, in quality of reviewer, at the following international conferences : IROS 2015, ICRA 2015.

### *10.1.3. Journal*

*10.1.3.1. Member of the editorial boards*

- C. Laugier is a member of the Editorial Board of the JSME Robomech Journal.

- C. Laugier is a member of the Editorial Board of the new IEEE Journal "Transaction of Intelligent Vehicles". He is member of the Steering Committee of the Journal and Senior Editor.
- O. Simonin was member of the editorial board of Robotics and Autonomous Systems Journal, for the Volume 75 Part A "Assistance and Service Robotics in a Human Environment", Jan. 2016.

*10.1.3.2. Reviewer - Reviewing activities*

- A. Martinelli served, in quality of reviewer, for the following journals: Foundation and Trend in Robotics, Transaction on Automation Science and Engineering
- Jilles S. Dibangoye served as a reviewer for the following journals: Journal on Artificial Intelligence Research (JAIR), Artificial Intelligence Journal (AIJ), IEEE Transactions on Robotics (TRO).
- O. Simonin serves, in quality of reviewer, for the RIA revue (Revue d'Intelligence Artificielle).

### 10.1.4. Invited talks

- C. Laugier was invited to give a talk at IET Workshop on "Autonomous Vehicles: from the theory to full scale applications", Novotel Paris Les Halles, Paris, June 18th 2015.
  Talk title: Risk Assessment and Decision-making for Safe Vehicle Navigation under Uncertainty.
- C. Laugier was invited to give a talk at RII "Smart Cities & Mobility Innovations", San Francisco, May 11th 2015.
  Talk title: Bayesian Perception and Decision for Intelligent Mobility.
- C. Laugier was invited to give a talk at Google Self-Driving Cars, Mountain View, May 12th 2015.
  Talk title: Bayesian Perception and Decision for next Cars Generation.
- C. Laugier was invited to give a Keynote talk at PPNIV-7 workshop, IEEE/RSJ IROS 2015, Hamburg, September 28th 2015.
  Talk title: Embedded Bayesian Perception and Risk Assessment for ADAS and Autonomous Cars.
- O. Simonin was invited to give a talk at JNRR 2015, Journées Nationales de la Recherche en Robotique, October 21-23, Cap Hornu.
- A. Spalanzani was invited to give a talk at the Colloque Jacques Cartier "Robotique, Services et Santé", 30th-1st of november/december, Lyon.

### 10.1.5. Leadership within the scientific community

- C. Laugier has been invited as co-author (with Alberto Broggi, Alex Zelinsky and Umit Ozguner) for the Chapter 62 on "Intelligent Vehicles" of the 2nd edition of the Handbook of Robotics (to appear on March 2016).

### 10.1.6. Scientific expertise

- C. Laugier is Scientific Consultant for the Probayes company.

### 10.1.7. Research administration

- C. Laugier is a member of several Ministerial and Regional French Committees on Robotics and Autonomous Cars.
- O. Simonin is member of the Rhone-Alpes Robotics cluster (Coboteam), for Inria and INSA de Lyon entities.
- A. Martinelli carried out the activity of leader for the ANR project VIMAD
- A. Martinelli carried out the activity of leader for the CARNOT project SEDIA

## 10.2. Teaching - Supervision - Juries

### 10.2.1. Teaching

M2R Informatique option RTS : O. Simonin, Robotique distribuée, 8h, M2, Université de Lyon, France.

INSA Lyon 5th year : O. Simonin, Robots mobiles communicants, 60h, M2, INSA de Lyon, France.

INSA Lyon 3rd year : O. Simonin, Algorithmique et programmation, 20h, L3, Dept. Telecom INSA de Lyon, France.

M2R MoSIG: A. Martinelli, Autonomous Robotics, 12h, ENSIMAG Grenoble

**E-learning**

Mooc "Mobile Robots and Autonomous Vehicles" (eMotion / Chroma): C. Laugier, A. Martinelli and D. Vasquez, 5 weeks on Inria-uTOP site, Videos in English including quiz, International diffusion on Inria-uTOP site, course for Engineers, Master and PhD students.

### *10.2.2. Supervision*

PhD in progress: Tiana Rakotovao Andriamahefa, Embedded Bayesian Perception on a Multi-core Architecture, 2013, C. Laugier and D. Ruspini (CEA LETI).

PhD in progress: David Sierra Gonzalez, Autonomous Driving, 2014, E. Mazer (Inria Prima), J. Dibangoye, C. Laugier (cooperation Toyota).

PhD in progress: Mathieu Barbier, Decision making for Intelligent Vehicles, 2015, O. E. Mazer (Inria Prima), O. Simonin, C. Laugier (cooperation Renault)

PhD in progress: Vishnu K. Narayanan, semi-autonomous navigation of a electric wheelchair using visual servoing and user intention analysis, 2013, M. Babel (Lagadic Team) and A. Spalanzani.

PhD in progress: Stefan Chitic, Middleware for multi-robot systems, 2013, O. Simonin, J. Ponge (CITI-Dynamid), Ministry funding.

Starting PhD: Mihai Popescu, Robot fleet mobility under communication constraints, O. Simonin, A. Spalanzani, Regional funding.

### *10.2.3. Juries*

- O. Simonin was a member of the defense committee of the HDR of Cedric Pradalier, INP Toulouse, June 5th, 2015.

- O. Simonin was a reviewer and a member of the defense committee of the HDR of Anne Spalanzani, Université Pierre-Mendès-France, June 22th, 2015.

- C. Laugier was a member of the defense committee of the HDR of Anne Spalanzani, Université Pierre-Mendès-France, June 22th, 2015.

- O. Simonin was a reviewer and a member of the defense committee of the PhD thesis of Bassem Hichri, Université Blaise Pascal, October, 2015.

- O. Simonin was a reviewer and a member of the defense committee of the PhD thesis of Zoubida Afoutni, Université de la Réunion, Montpellier September 25th, 2015.

- O. Simonin was a reviewer and a member of the defense committee of the PhD thesis of Cyril Robin, Université de Toulouse, June 4th, 2015.

- O. Simonin was a member of the selection committee (COS) for an Associate Professor position at Université de Grenoble, IUT de Valence.

- A. Spalanzani was a reviewer and a member of the defense committee of the PhD thesis of Mihai Andries, Université de Lorraine, December 15th, 2015.

- C. Laugier was a reviewer and a member of the defense committee of the PhD thesis of Thibaut Kruse, Technical University of Munich, January 14th, 2015.

- C. Laugier was President of the Jury of the French PhD Theses Award 2015 of the GDR Robotique (Theses defended in 2014), Presented at the JNRR 2015, 21-23 October 2015, Cap Hornu.

# 11. Bibliography

## Publications of the year

### Articles in International Peer-Reviewed Journals

[1] M. ANDRIES, O. SIMONIN, F. CHARPILLET. *Localisation of humans, objects and robots interacting on load-sensing floors*, in "IEEE Sensors Journal", 2015, vol. PP, n$^{o}$ 99, 12 p. [*DOI :* 10.1109/JSEN.2015.2493122], https://hal.inria.fr/hal-01196042

[2] J. S. DIBANGOYE, D. ARNAUD, H. FAKHAM, F. COLAS, X. GUILLAUD. *Distributed economic dispatch of embedded generation in smart grids*, in "Engineering Applications of Artificial Intelligence", May 2015, 24 p. , https://hal.inria.fr/hal-01188482

[3] N. KALDÉ, O. SIMONIN, F. CHARPILLET. *Comparison of Classical and Interactive Multi-Robot Exploration Strategies in Populated Environments*, in "Acta-Polytechnica,-Czech-Technical-University-in-Prague", June 2015, vol. 55, n$^{o}$ 3, pp. 154-161, https://hal.archives-ouvertes.fr/hal-01191456

[4] C. TROIANI, A. MARTINELLI, C. LAUGIER, D. SCARAMUZZA. *Low computational-complexity algorithms for vision-aided inertial navigation of micro aerial vehicles*, in "Robotics and Autonomous Systems", July 2015, https://hal.inria.fr/hal-01248800

### Articles in Non Peer-Reviewed Journals

[5] P. LUCIDARME, O. SIMONIN. *Cartographie et localisation simultanées multirobots*, in "Techniques de l'Ingenieur", May 2015, n$^{o}$ s7738, 17 p. , https://hal.archives-ouvertes.fr/hal-01162117

### Invited Conferences

[6] O. SIMONIN. *Coopération multi-robot : enjeux et défis scientifiques*, in "Journées Nationales de la Recherche en Robotique (JNRR)", Cap Hornu, France, October 2015, https://hal.archives-ouvertes.fr/hal-01246801

### International Conferences with Proceedings

[7] M. ANDRIES, F. CHARPILLET, O. SIMONIN. *High resolution pressure sensing using sub-pixel shifts on low resolution load-sensing tiles*, in "2015 IEEE International Conference on Robotics and Automation (ICRA 2015)", Seattle, United States, May 2015, https://hal.inria.fr/hal-01136255

[8] J. COHEN, L. MATIGNON, O. SIMONIN. *Concentric and Incremental Multi-Robot Mapping to Observe Complex Scenes*, in "IROS 2015 Workshop on On-line decision-making in multi-robot coordination (DEMUR'15)", Hamburg, Germany, October 2015, https://hal.archives-ouvertes.fr/hal-01254964

[9] S. LEFÈVRE, D. VASQUEZ, C. LAUGIER, J. IBAÑEZ-GUZMAN. *Intention-aware risk estimation: Field results*, in "IEEE International Workshop on Advanced Robotics and its Social Impacts", Lyon, France, July 2015, https://hal.inria.fr/hal-01211563

[10] L. RUMMELHARD, A. NEGRE, C. LAUGIER. *Conditional Monte Carlo Dense Occupancy Tracker*, in "18th IEEE International Conference on Intelligent Transportation Systems", Las Palmas, Spain, September 2015, https://hal.inria.fr/hal-01205298

[11] J. SARAYDARYAN, F. JUMEL, O. SIMONIN. *Robots Delivering Services to Moving People : Individual vs. Group Patrolling Strategies*, in "The 2015 IEEE International Workshop on Advanced Robotics and its Social Impacts (ARSO 2015)", Lyon, France, IEEE, July 2015, https://hal.archives-ouvertes.fr/hal-01191457

[12] D. VASQUEZ. *Novel Planning-based Algorithms for Human Motion Prediction*, in "IEEE Conference on Robotics and Automation", Stockholm, Sweden, May 2016, forthcoming, https://hal.inria.fr/hal-01256516

### Conferences without Proceedings

[13] J. S. DIBANGOYE, C. AMATO, O. BUFFET, F. CHARPILLET. *Exploiting separability in multiagent planning with continuous-state mdps (extended abstract)*, in "Proceedings of the twenty-fourth international joint conference on artificial intelligence, IJCAI 2015", Buenos Aires, Argentina, July 2015, https://hal.inria.fr/hal-01188483

[14] J. S. DIBANGOYE, O. BUFFET, O. SIMONIN. *Structural results for cooperative decentralized control models*, in "Proceedings of the twenty-fourth international joint conference on artificial intelligence, IJCAI 2015", Buenos Aires, Argentina, July 2015, https://hal.inria.fr/hal-01188481

[15] J. LUSSEREAU, P. STEIN, J.-A. DAVID, L. RUMMELHARD, A. NEGRE, C. LAUGIER, N. VIGNARD, G. OTHMEZOURI. *Integration of ADAS algorithm in a Vehicle Prototype*, in "IEEE International Workshop on Advanced Robotics and its Social Impacts ARSO 2015", LYON, France, July 2015, https://hal.inria.fr/hal-01212431

[16] A. MARTINELLI. *Extension of the observability rank condition to nonlinear systems driven by unknown inputs*, in "MED 2015", Torremolinos, Spain, June 2015 [*DOI :* 10.1109/MED.2015.7158811], https://hal.inria.fr/hal-01248783

[17] A. MARTINELLI. *Minimalistic sensor design in visual-inertial structure from motion*, in "icra 2015", Seattle, United States, May 2015 [*DOI :* 10.1109/ICRA.2015.7139656], https://hal.inria.fr/hal-01248785

[18] A. MARTINELLI. *Nonlinear Unknown Input Observability: Analytical expression of the observable codistribution in the case of a single unknown input*, in "SIAM - CT15", Paris, France, July 2015 [*DOI :* 10.1137/1.9781611974072.2], https://hal.inria.fr/hal-01248792

[19] T. RAKOTOVAO, J. MOTTIN, D. PUSCHINI, C. LAUGIER. *Real-Time Power-Efficient Integration of Multi-Sensor Occupancy Grid on Many-Core*, in "IEEE International Workshop on Advanced Robotics and its Social Impacts. ARSO 2015", Lyon, France, July 2015, https://hal-cea.archives-ouvertes.fr/cea-01176446

### Scientific Books (or Scientific Book chapters)

[20] A. BROGGI, A. ZELINSKY, U. OZGUNER, C. LAUGIER. *Intelligent Vehicles*, in "Handbook of Robotics 2nd Edition", B. SICILIANO, O. KHATIB (editors), April 2016, https://hal.inria.fr/hal-01260280

### Other Publications

[21] C. LAUGIER. *Bayesian Perception and Decision for Intelligent Mobility*, May 2015, Invited talk at Inria Industry Meeting (RII) on "Smart Cities & Mobility Innovations: Towards Environmental and Social Sustainability", San Francisco, May 2015., https://hal.inria.fr/hal-01264198

[22] C. LAUGIER. *Bayesian Perception and Decision Making for next Cars Generation*, May 2015, Invited talk at Google Self-Driving Cars, Mountain View, May 12th 2015, https://hal.inria.fr/hal-01264215

[23] C. LAUGIER. *Embedded Bayesian Perception and Risk Assessment for ADAS and Autonomous Cars*, September 2015, Keynote talk at PPNIV-7 Workshop, IEEE/RSJ IROS 2015, September 28th 2015, Hamburg, https://hal.inria.fr/hal-01264200

[24] C. LAUGIER. *Risk Assessment and Decision-Making for Safe Vehicle Navigation under Uncertainty*, June 2015, Invited talk at IET (The Institution of Engineering and Technology) Workshop "Autonomous vehicles: From Theory to Full Scale Applications". Video can be found at https://tv.theiet.org/?videoid=6974, https://hal.inria.fr/hal-01260282

[25] C. LAUGIER, A. MARTINELLI, D. A. VASQUEZ. *Mooc Mobile Robots and Autonomous Vehicles*, May 2015, Lecture - International Mooc Course from Inria-uTOP. First edition in May 2015, second edition in February 2016, https://hal.inria.fr/cel-01256021

## References in notes

[26] P. ABBEEL, A. NG. *Apprenticeship learning via inverse reinforcement learning*, in "Proceedings of the 21st international conference on machine learning", 2004 [*DOI :* 10.1145/1015330.1015430], http://www.eecs.harvard.edu/~parkes/cs286r/spring06/papers/abeelng.pdf

[27] M. ANDRIES. *Object and human tracking, and robot control through a load sensing floor*, PhD., Université de Lorraine, December 2015, https://hal.inria.fr/tel-01252938

[28] C. COUÉ, C. PRADALIER, C. LAUGIER, T. FRAICHARD, P. BESSIÈRE. *Bayesian Occupancy Filtering for Multi-Target Tracking: an Automotive Application*, in "Int. Journal of Robotics Research", January 2006, vol. 25, n$^{o}$ 1, pp. 19–30

[29] A. ELFES. *Occupancy grids: A probabilistic framework for robot perception and navigation*, 1989

[30] J. FAIGL, O. SIMONIN, F. CHARPILLET. *Comparison of Task-Allocation Algorithms in Frontier-Based Multi-Robot Exploration*, in "12th European Conference on Multi-Agent Systems", Prague, Czech Republic, Springer, December 2014, https://hal.archives-ouvertes.fr/hal-01081853

[31] C. FULGENZI, A. SPALANZANI, C. LAUGIER. *Dynamic Obstacle Avoidance in uncertain environment combining PVOs and Occupancy Grid*, in "Proceedings of IEEE International Conference on Robotics and Automation (ICRA)", 2007, pp. 1610–1616

[32] C. FULGENZI, C. TAY, A. SPALANZANI, C. LAUGIER. *Probabilistic navigation in dynamic environment using Rapidly-exploring Random Trees and Gaussian Processes*, in "IEEE/RSJ 2008 International Conference on Intelligent RObots and Systems", France Nice, 2008, http://hal.inria.fr/inria-00332595/en/

[33] Y. JIA, E. SHELHAMER, J. DONAHUE, S. KARAYEV, J. LONG, R. GIRSHICK, S. GUADARRAMA, T. DARRELL. *Caffe: Convolutional Architecture for Fast Feature Embedding*, in "arXiv preprint arXiv:1408.5093", 2014

[34] K. M. KITANI, B. D. ZIEBART, J. A. BAGNELL, M. HEBERT. *Activity Forecasting*, in "European Conference on Computer Vision", 2012, vol. 7575, pp. 201–214

[35] A. KRIZHEVSKY, I. SUTSKEVER, G. E. HINTON. *ImageNet Classification with Deep Convolutional Neural Networks*, in "Advances in Neural Information Processing Systems 25", F. PEREIRA, C. BURGES, L. BOTTOU, K. WEINBERGER (editors), Curran Associates, Inc., 2012, pp. 1097–1105, http://papers.nips.cc/paper/4824-imagenet-classification-with-deep-convolutional-neural-networks.pdf

[36] C. LAUGIER, I. PAROMTCHIK, M. PERROLLAZ, Y. MAO, J.-D. YODER, C. TAY, K. MEKHNACHA, A. NÈGRE. *Probabilistic Analysis of Dynamic Scenes and Collision Risk Assessment to Improve Driving Safety*, in "Intelligent Transportation Systems Magazine", November 2011, vol. 3, n° 4, http://hal.inria.fr/hal-00645046/en/

[37] Y. LECUN, L. BOTTOU, Y. BENGIO, P. HAFFNER. *Gradient-based learning applied to document recognition*, in "Proceedings of the IEEE", 1998, vol. 86, n° 11, pp. 2278–2324

[38] S. LEFÈVRE, R. BAJCSY, C. LAUGIER. *Probabilistic Decision Making for Collision Avoidance Systems: Postponing Decisions*, in "IEEE/RSJ International Conference on Intelligent Robots and Systems", Tokyo, Japan, 2013, https://hal.inria.fr/hal-00880440

[39] S. LEFÈVRE, D. VASQUEZ, C. LAUGIER. *A survey on motion prediction and risk assessment for intelligent vehicles*, in "Robomech", July 2014, vol. 1, n° 1

[40] A. MARTINELLI. *State Estimation based on the Concept of Continuous Symmetry and Observability Analysis: The Case of Calibration*, in "IEEE Transactions on Robotics", May 2011, http://hal.inria.fr/hal-00578795/en

[41] A. MARTINELLI. *Vision and IMU Data Fusion: Closed-Form Solutions for Attitude, Speed, Absolute Scale and Bias Determination*, in "Transaction on Robotics", 2012, vol. 28, n° 1

[42] A. MARTINELLI. *Closed-form solution of visual-inertial structure from motion*, in "International Journal of Computer Vision", August 2013, online, https://hal.archives-ouvertes.fr/hal-00905881

[43] A. MARTINELLI. *Observabilty Properties and Deterministic Algorithms in Visual-Inertial Structure from Motion*, in "Foundations and Trends in Robotics (FnTROB)", December 2013, pp. 1–75 [*DOI :* 10.1088/1742-5468/2014/03/P03003], https://hal.inria.fr/hal-01096948

[44] A. MARTINELLI. *Closed-Form Solution of Visual Inertial Structure from Motion*, in "International Journal of Computer Vision", 2014, vol. 106, n° 2, pp. 138-152

[45] D. MEIGNAN, O. SIMONIN, A. KOUKAM. *Simulation and Evaluation of Urban Bus Networks using a Multiagent Approach*, in "Simulation Modelling Practice and Theory", 2007, vol. 15, n° 6, pp. 659-671 [*DOI :* 10.1016/J.SIMPAT.2007.02.005], https://hal.inria.fr/inria-00172340

[46] A. NÈGRE, L. RUMMELHARD, C. LAUGIER. *Hybrid Sampling Bayesian Occupancy Filter*, in "IEEE Intelligent Vehicles Symposium (IV)", Dearborn, United States, June 2014, https://hal.inria.fr/hal-01011703

[47] L. RUMMELHARD, A. NEGRE, C. LAUGIER. *Conditional Monte Carlo Dense Occupancy Tracker*, in "18th IEEE International Conference on Intelligent Transportation Systems", Las Palmas, Spain, September 2015, https://hal.inria.fr/hal-01205298

[48] L. RUMMELHARD, A. NÈGRE, M. PERROLLAZ, C. LAUGIER. *Probabilistic Grid-based Collision Risk Prediction for Driving Application*, in "ISER", Marrakech/Essaouira, Morocco, June 2014, https://hal.inria.fr/hal-01011808

[49] J. A. SETHIAN. *Fast marching methods*, in "SIAM review", 1999, vol. 41, n$^{o}$ 2, pp. 199–235

[50] O. SIMONIN, F. CHARPILLET, E. THIERRY. *Revisiting wavefront construction with collective agents: an approach to foraging*, in "Swarm Intelligence", June 2014, vol. 8, n$^{o}$ 2, pp. 113-138 [*DOI :* 10.1007/s11721-014-0093-3], https://hal.inria.fr/hal-00974068

[51] A. SPALANZANI, J. RIOS-MARTINEZ, C. LAUGIER, S. LEE. *Risk Based Navigation Decisions*, in "Handbook of Intelligent Vehicles", A. ESKANDARIAN (editor), Springer Verlag, February 2012, vol. 1, http://hal.inria.fr/hal-00743336

[52] C. TAY, C. LAUGIER. *Modelling Smooth Paths Using Gaussian Processes*, in "International Conference on Field and Service Robotics", 2007, https://hal.inria.fr/inria-00181664/en/

[53] S. THRUN, W. BURGARD, D. FOX. *Probabilistic Robotics*, The MIT Press, 2005

[54] M. TLIG, O. BUFFET, O. SIMONIN. *Stop-Free Strategies for Traffic Networks: Decentralized On-line Optimization*, in "21th European Conference on Artificial Intelligence ECAI 2014", Prague, Czech Republic, IOS Press, August 2014, pp. 1191 - 1196, https://hal.archives-ouvertes.fr/hal-01232023

[55] D. VASQUEZ, B. OKAL, K. O. ARRAS. *Inverse Reinforcement Learning Algorithms and Features for Robot Navigation in Crowds: an experimental comparison*, in "IEEE-RSJ Int. Conf. on Intelligent Robots and Systems", 2014

[56] D. VASQUEZ, Y. YU, S. KUMAR, C. LAUGIER. *An open framework for human-like autonomous driving using Inverse Reinforcement Learning*, in "IEEE Vehicle Power and Propulsion Conference", 2014

[57] D. A. VASQUEZ GOVEA, T. FRAICHARD, C. LAUGIER. *Growing Hidden Markov Models: An Incremental Tool for Learning and Predicting Human and Vehicle Motion*, in "International Journal of Robotics Research", 2009, vol. 28, n$^{o}$ 11-12, pp. 1486-1506, http://hal.inria.fr/inria-00430582/en/

[58] B. D. ZIEBART, A. L. MAAS, J. A. BAGNELL, A. K. DEY. *Maximum Entropy Inverse Reinforcement Learning*, in "Proceedings of the Twenty-Third AAAI Conference on Artificial Intelligence, AAAI 2008, Chicago, Illinois, USA, July 13-17, 2008", 2008, pp. 1433–1438, http://www.aaai.org/Library/AAAI/2008/aaai08-227.php