Activity Report 2016

Team CHROMA

Cooperative and Human-aware Robot Navigation in Dynamic Environments

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

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Team CHROMA

Creation of the Team: 2015 March 01

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Computer Science and Digital Science:

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Other Research Topics and Application Domains:

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1. Members

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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 decision-making issues in mobile robotics and who share common approaches that mainly relates to the field of artificial intelligence. The group is gathering some members of the previous eMotion Inria project-team led by Christian Laugier (2002-2014) and of teacher-researchers from INSA [1] [2] Lyon working in the robotic group led by Prof. Olivier Simonin in CITI Lab. [3] (since 2013). The team is distributed on two sites : the Centre Inria Grenoble and the INSA Lyon campus.

The Chroma group was initially composed of Olivier Simonin (Prof. INSA Lyon), Christian Laugier (Inria researcher DR1), Jilles Dibangoye (Asso. Prof. INSA Lyon), Agostino Martinelli (Inria researcher CR1) and Dizan Vasquez (Inria starting researcher SRP). On December 1, 2015, Anne Spalanzani (Asso. Prof. Univ. Grenoble, habilite) has joined the group (she was previously in Prima and eMotion Inria teams). In January 2016, Dizan Vasquez has left 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” [4] and “Multi-Robot Systems (MRS) [5]"

[1] National Institute of Applied Sciences
[2] INSA Lyon is part of the Université de Lyon
[3] Centre of Innovation in Telecommunications and Integration of Service, see http://www.citi-lab.fr/
[4] 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
[5] IEEE RAS Multi-Robot Systems http://multirobotsystems.org/

More precisely, our goal is to design algorithms and develop models allowing mobile robots to navigate and cooperate in dynamic and human-populated environments. Chroma is involved in all decision aspects pertaining to single 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 safely among humans in partially known environments, where time, dynamics and interactions play a major role. Recent advances 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 clearly positioned in the third challenge of the **Inria 2013-2017 Strategic Plan "Interacting with the real and digital worlds: interaction, uses and learning"**.

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 sociology for the purpose of taking into account human models. Two main research themes of mobile robotics are addressed : i) Perception and situation awareness ii) Navigation and Cooperation in Dynamic Environments. Next, we elaborate more about these two research axes.

- **Perception and Situation Awareness.** 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:
  - **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) ?
  - **Robust state estimation**: acquire a deep understanding on several sensor fusion problems and investigate their observability properties in the case of unknown inputs.
- **Navigation and Cooperation in Dynamic Environments.** The challenge is to build models allowing robots to move and to coordinate efficiently in dynamic environments. We focus on two problems : navigation in human-populated environment (social navigation) and cooperation in large distributed fleet of robots (scalability and robustness issues).
  - **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, or to learn them, and planning algorithms that take into account them.
  - **Decision Making in Multi-robot systems.** 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 Intelligence (SI).

The Chroma project is also concerned with applications and transfer of the scientific results. Our main application domains concern autonomous connected vehicles and service robotics. They are presented in Sections 4.2 and 4.3. Chroma have currently projects developed with industrial (as Renault and Toyota) and startup partners.

3. Research Program

3.1. Introduction

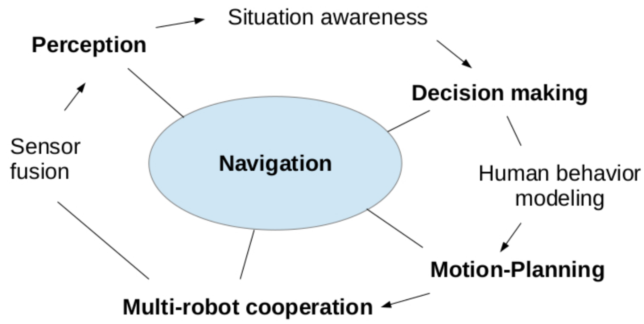

Figure 1. Research themes of the team and their relation

The Chroma team aims to deal with different issues of autonomous mobile robotics : perception, decision-making and cooperation. Figure 1 schemes the different themes and sub-themes investigated by Chroma.

We present here after our approaches to address these different theme of research, and how they combine to contribute to the general problem of robotic navigation. Chroma pays particular attention to current challenges that are autonomous navigation in highly dynamic environments populated by humans and cooperation in (large) multi-robot systems. These challenges are common with other major robotic laboratories/teams in the world, such as Autonomous Systems Lab at ETH Zurich, Robotic Embedded Systems Laboratory at USC, KIT [6] (Prof Christoph Stiller lab and Prof Ruediger Dillmann lab), UC Berkeley, Vislab Parma (Prof. Alberto Broggi), iCeiRA [7] laboratory in Taipei. Chroma is collaborating at various levels (visits, postdocs, research projects, common publications, etc.) with most of these laboratories, see Sections 9.3 and 9.4.

3.2. Perception and Situation Awareness

Participants: Christian Laugier, Agostino Martinelli, Jilles S. Dibangoye, Anne Spalanzani, Olivier Simonin.

Robust perception 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 these problems, mainly because such environments are uncontrolled [8] and exhibit strong constraints to be satisfied (in particular high dynamicity and 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**.

3.2.1. Bayesian perception

Context and previous work. Perception is known to be one of the main bottleneck for robot motion autonomy, in particular when navigating in open and dynamic environments is subject to strong real-time and uncertainty constraints. Traditional object-level solutions [9] still exhibit a lack of efficiency and of robustness when operating in such complex environments. In order to overcome this difficulty, we have proposed in the scope of the former e-Motion team, 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 [42] and further developed in the team [58] [10].

[6] Karlsruhe Institut fur Technologie
[7] International Center of Excellence in Intelligent Robotics and Automation Research.
[8] partially unknown and open
[9] object recognition based on image processing
[10] The *Bayesian programming formalism* developed in e-Motion, pioneered (together with the contemporary work of Thrun, Burgards and Fox [94]) a systematic effort to formalize robotics problems under Probability theory –an approach that is now pervasive in Robotics.

Figure 2. Illustrations of the HSBOF model and experiment with the Zoe car

The basic idea is to combine a Bayesian filter with a probabilistic grid representation of both the space and the motions, see illustration Fig. 2. This new approach can be seen as an extension for uncertain dynamic scenes, of the initial concept of "Occupancy Grid" proposed in 1989 by Elfes [11]. It allows the filtering and the fusion of heterogeneous and uncertain sensors data, by taking into account the history of the sensors measurements, a probabilistic model of the sensors and of the uncertainty, and a dynamic model of the observed objects motions.

In the scope of the Chroma team and of several academic and industrial projects, we went on with the development and the extension under strong embedded implementation constraints, of our Bayesian Perception concept. This work has already led to the development of more powerful models and more efficient implementations, e.g. the *HSBOF* [12] approach [76] and the *CMCDOT* [13] framework [84] which is still under development.

Current and future work address the extension of this model and its software implementation.

Objective — Extending the Bayesian Perception paradigm to the object level — We aim at defining a complete framework extending the Bayesian Perception paradigm to the object level. The main objective is to be simultaneously more robust, more efficient for embedded implementations, and more informative for the subsequent scene interpretation step.

We propose to integrate in a robust way higher level functions such as multiple objects detection and tracking or objects classification. The idea is to avoid well known object level detection errors and data association problems, by simultaneously reasoning at the *grid level* and at the *object level* by extracting / identifying / tracking / classifying clusters of dynamic cells (first work has been published in [84]).

Software development : new approaches for software / hardware integration The objective is to improve the efficiency of the approach (by exploiting the highly parallel characteristic of our approach), while drastically reducing important factors such as the required memory size, the size of the hardware component, its price and the required energy consumption. This work is absolutely necessary for studying *embedded solutions* for the future generation of mobile robots and autonomous vehicles.

3.2.2. Situation Awareness and Prediction

Context. Prediction of the evolution of the perceived actors is an important ability required for navigation in dynamic and uncertain environments, in particular to allow on-line safe decisions. We have recently shown that an interesting property of the Bayesian Perception approach is to generate short-term conservative [14] predictions on the likely future evolution of the observed scene, even if the sensing information is temporary incomplete or not available [76]. 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.

[11] A. Elfes."Occupancy grids: A probabilistic framework for robot perception and navigation", Ph.D. dissertation, Carnegie Mellon University, Pittsburgh, USA, 1989.
[12] Hybrid Sampling Bayesian Occupancy Filter
[13] Conditional Monte Carlo Dense Occupancy Tracker
[14] i.e. when motion parameters are supposed to be stable during a small amount of time

Objective We aim to develop 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 [98], Gaussian Processes [92]). A strong challenge of prediction in multiple moving agents environments is to take into consideration the interactions between the different agents (traffic participants). Existing interaction-aware approaches estimate exhaustively the intent of all road users [59], assume a cooperative behavior [88], or learn the policy model of drivers using supervised learning [50]. In contrast, we adopt a *planning-based motion prediction approach*, which is a framework to predict human behavior [102], [56][27]. Planning-based approaches assume that humans, when they perform a task, they do so by minimizing a cost function that depends on their preferences and the context. Such a cost function can be obtained, for example, from demonstrations using *Inverse Reinforcement Learning* [75], [36]. This constitutes an intuitive approach and, more importantly, enables us to overcome the limitations of other approaches, namely, high complexity [59], unrealistic assumptions [88], and overfitting [50]. We have recently demonstrated the predictive potential of our approach in [26].

Towards an On-line Bayesian Decision-Making framework. The team aims at building a general framework for perception and decision-making in multi-robot/vehicle environments. The navigation will be performed under both dynamic and uncertainty constraints, with contextual information and a continuous analysis of the evolution of the probabilistic collision risk (see above). Results have recently been obtained in cooperation with Renault and Berkeley, by using the "Intention / Expectation" paradigm and Dynamic Bayesian Networks; these results have been published in [60], [61] and patented.

We are currently working on the generalization of this approach, in order to take into account the dynamics of the vehicles and multiple traffic participants. The objective is to design a new framework, allowing to overcome the shortcomings of rules-based reasoning approaches usually showing good results [64] [49], but leading to a lack of scalability and long terms predictions. Our research work is carried out through several cooperative projects (Toyota, Renault, project Prefect of IRT Nanoelec, European project ECSEL Enable-S3) and related PhD theses.

3.2.3. Robust state estimation (Sensor fusion)

Context. In order to safely and autonomously navigate in an unknown environment, a mobile robot is required to estimate in real time several physical quantities (e.g., position, orientation, speed). These physical quantities are often included in a common state vector and their simultaneous estimation is usually achieved by fusing the information coming from several sensors (e.g., camera, laser range finder, inertial sensors). The problem of fusing the information coming from different sensors is known as the *Sensor Fusion* problem and it is a fundamental problem which plays a major role in robotics.

Objective. A fundamental issue to be investigated in any sensor fusion problem is to understand whether the state is observable or not. Roughly speaking, we need to understand if the information contained in the measurements provided by all the sensors allows us to carry out the estimation of the state. If the state is not observable, we need to detect a new observable state. 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 some new theoretical concepts we introduced in [68] (concept of continuous symmetry). Additionally, we want to account the presence of disturbances in the observability analysis.

Our approach is to 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). We recently obtained a simple analytic tool able to account the presence of unknown inputs [71], which extends a heuristic solution derived by the team of Prof. Antonio Bicchi [40] with whom we collaborate (Centro Piaggio at the University of Pisa).

Fusing visual and inertial data. A special attention is devoted to the fusion of inertial and monocular vision sensors (which have strong application for instance in UAV navigation). The problem of fusing visual and inertial data has been extensively investigated in the past. However, most of the proposed methods require a state initialization. Because of the system nonlinearities, lack of precise initialization can irreparably damage the entire estimation process. In literature, this initialization is often guessed or assumed to be known [38], [63], [46]. Recently, this sensor fusion problem has been successfully addressed by enforcing observability constraints [51], [52] and by using optimization-based approaches [62], [45], [66], [53], [74]. These optimization methods outperform filter-based algorithms in terms of accuracy due to their capability of relinearizing past states. On the other hand, the optimization process can be affected by the presence of local minima. We are therefore interested in a deterministic solution that analytically expresses the state in terms of the measurements provided by the sensors during a short time-interval.

For some years we explore deterministic solutions as presented in [69] and [70]. Our objective is to improve the approach by taking into account the biases that affect low-cost inertial sensors (both gyroscopes and accelerometers) and to exploit the power of this solution for real applications. This work is currently supported by the ANR project VIMAD [15] and experimented with a quadrotor UAV. We have a collaboration with Prof. Stergios Roumeliotis (the leader of the MARS lab at the University of Minnesota) and with Prof. Anastasios Mourikis from the University of California Riverside. Regarding the usage of our solution for real applications we have a collaboration with Prof. Davide Scaramuzza (the leader of the Robotics and Perception group at the University of Zurich) and with Prof. Roland Siegwart from the ETHZ.

3.3. Navigation and cooperation in dynamic environments

Participants: Olivier Simonin, Anne Spalanzani, Jilles S. Dibangoye, Christian Laugier, Laetitia Matignon, Fabrice Jumel, Jacques Saraydaryan.

In his reference book *Planning algorithms* [16] 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, we aim at **scale up decision-making in human-populated environments and in multi-robot systems, while dealing with the intrinsic limits of the robots (computation capacity, limited communication)**.

3.3.1. Motion-planning in human-populated environment

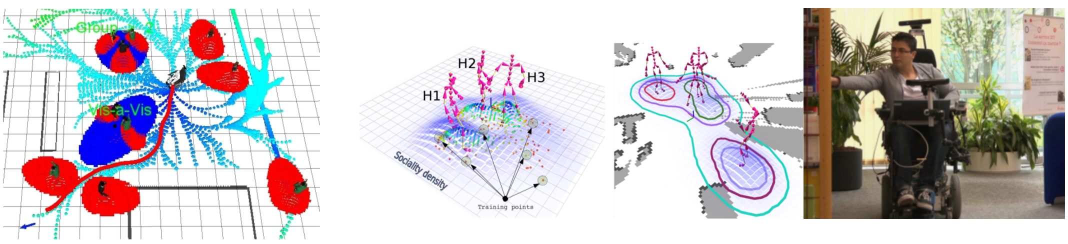

Figure 3. Illustrations of a. the Risk-RRT planning b. the human interaction space model c. experiment with the wheelchair.

[15] Navigation autonome des drones aériens avec la fusion des données visuelles et inertielles, lead by A. Martinelli, Chroma.
[16] Steven M. LaValle, Planning Algorithms, Cambridge University Press, 2006.

Context. Motion planning in dynamic and human-populated environments is a current challenge of robotics. Many research teams work on this topic. We can cite the Institut of robotic in Barcelone [44], the MIT [37], the Autonomous Intelligent Systems lab in Freiburg [41], or the LAAS [77]. In Chroma, we explore different issues : **integrating the risk (uncertainty) in planning processes, modeling and taking into account human behaviors and flows.**

Objective We aim to give the robot some socially compliant behaviors by anticipating the near future (trajectories of mobile obstacle in the robot's surroundings) and by integrating knowledge from psychology, sociology and urban planning. In this context, we will focus on the following 3 topics.

Risk-based planning. Unlike static or controlled environments [17] where global path planning approaches are suitable, dealing with highly dynamic and uncertain environments requires to integrate the notion of risk (risk of collision, risk of disturbance). This risk can be computed by methods proposed in the section 3.2.2. Then, we examine how motion planning approaches can integrate this risk in the generation and selection of the paths. An algorithm called RiskRRT was proposed in the eMotion team. This algorithm plans goal oriented trajectories that minimize the risk estimated at each instant. It fits environments that are highly dynamic and adapts to a representation of uncertainty [90] (see Figure 3.a for illustration). Now, we aim to extend this principle to be adapted to various risk evaluation methods (proposed in 3.2) and various situation (highways, urban environments, even in dense traffic or in crowds).

Sharing the physical space with humans. Robots are expected to share their 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, that is why they must follow social conventions, respecting proximity constraints, avoiding people interacting or joining a group engaged in conversation without disturbing. For this purpose, we proposed earlier to integrate some knowledge from the psychology domain (i.e. proxemics theory), see figure 3.b. We aim now to integrate semantic knowledge [18] and psycho-social theories of human behavior [19] [20] in the navigation framework we have developed for a few years (i.e. the Risk-based navigation algorithms [48], [90], [97]). These concepts were tested on our automated wheelchair (see figure 3.c) but they have and will be adapted to autonomous cars, telepresence robots and companion robots. This work is currently supported by the ANR Valet, the TENSIVE project and the Associated team Sampen (with Iceira Lab, Taipei).

Mapping human flows. We investigate the problem of modeling recurring human displacements to improve robots navigation in such dense populated environments. It has been shown that such recurring behaviours can be mapped from spatial-temporal observations, as in [95]. In this context we address the problem of mapping human flows from robot(s) perception. We started to propose counting-based mapping models [30] that contain motion probabilities in the grid cells. Then such a grid can be exploited to define path-planning functions (eg. A* based) that take into account the probability to encounter humans in opposite direction. We also aim at demonstrating the efficiency of the approach whith real robots evolving in dense human-populated environments.

3.3.2. Decision Making in Multi-robot systems

Context. A central challenge in Chroma is to define **decision-making algorithms that scale up to large multi-robot systems**. This work takes place in the general framework of Multi-Agent Systems (MAS). The objective is to compute/define agent behaviors that provide cooperation and adaptation abilities. Solutions must also take into account the agent/robot computational limits.

We can abstract the challenge in three objectives :
i) mastering the complexity of large fleet of robots/vehicles (scalability),

[17] known environment without uncertainty
[18] B. Kuipers, The Spatial Semantic Hierarchy, Artificial Intelligence, Volume 119, Issues 1–2, May 2000, Pages 191-233
[19] 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.
[20] Hall, E. (1966). The hidden dimension. Doubleday Anchor Books.

ii) dealing with limited computational/memory capacity
iii) building adaptive solutions (robustness).

Combining Decision-theoretic models and Swarm intelligence.

Over the past few years, our attempts to address multi-robot decision-making are mainly due to Multi-Agent Sequential Decision Making (MA-SDM) and Swarm Intelligence (SI). 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. In contrast, the expressiveness of MA-SDM models has limited scalability in face of realistic multi-robot systems [21], resulting in computational overload. On their side, SI methods, which rely on local rules – generally bio-inspired – and relating to Self-Organized Systems [22], can scale up to multiple robots and provide robustness to disturbances, but with poor theoretical guarantees [23]. Swarm models can also answer to the need of designing tractable solutions [89], but they remain not geared to express complex realistic tasks or to handle (point-to-point) communication between robots. This motivates our work to go beyond these two approaches and to combine them.

First, we plan to investigate **incremental expansion mechanisms in anytime decision-theoretic planning**, starting from local rules (from SI) to complex strategies with performance guarantees (from MA-SDM) [43]. 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 SI approach by considering **the integration of optimization techniques at the local level**. 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 (or using learning techniques). The main optimization methods we will consider are Local Search (Gradient Descent), Distributed Stochastic Algorithm and Reinforcement Learning. We have shown in [96] the interest of such an approach for driverless vehicle traffic optimization. In 2016, we started a new PHD in collaboration with the VOLVO Group to deal with global-local optimization for goods distribution using a fleet of autonomous vehicles.

Both approaches must lead to **master the complexity** inherent to large and open multi-robot systems. Such systems are prone to combinatorial problems, in term of state space and communication, when the number of robots grows. To cope with this complexity we started to develop a methodology which relies on incrementally refining the environment representation while the robots perform their tasks.

Mastering the computational cost involved in cooperative decision-making relies also on building heuristics. We explore how exact (global) solutions can be decentralized in local computation allocated to group of robots or to each robot. We started to apply this methodology to dynamic problems such as the patrolling of moving persons (see [87]).

Beyond this methodological work, we aim to evaluate our models on benchmarks from the literature, by using simulation tools as a complement of robotic experiments. This will lead us to develop simulators, allowing to deploy thousands of humans and robots in constrained environments.

Towards adaptive connected robots.

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

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

[23] S. A. Brueckner, G. Di Marzo Serugendo, A. Karageorgos, R. Nagpal (2005). Engineering Self-Organising Systems, Methodologies and Applications. LNAI 3464 State-of-the-Art Survey, Springer book.

Mobile robots and autonomous vehicles are becoming more connected to one another and to other devices in the environment (concept of cloud of robots [24] and V2V/V2I connectivity in transportation systems). Such robotic systems are open systems as the number of connected entities is varying dynamically. Network of robots brought with them new problems, as the need of (online) adaption to changes in the system and to the variability of the communication.

In Chroma, we address the problem of adaptation by considering machine learning techniques and local mechanisms as discussed above (SI models). More specifically we investigate the problem of maintaining the connectivity between robots which perform dynamic version of tasks such as patrolling, exploration or transportation, i.e. where the setting of the problem is constinuously changing and growing (see [25]).

Robot fleets should be able to adapt their behavior and organisation to communication limits and variation. It has been shown that wireless communication are very changing in time and space [65]. So we explore how robots can optimize their behaviors by perceiving and learning the quality of their communication in the environment. In Lyon, the CITI Lab. conducts research in many aspects of telecommunication, from signal theory to distributed computation. In this context, Chroma develops cooperations with the Inria team Urbanet [25] (wireless communication protocols) and with the Dynamid team [19] (middlleware and cloud aspects), that we wish to reinforce in the next years.

4. Application Domains

4.1. Introduction

Applications in Chroma are organized in two main domains : **i) Future cars and transportation systems and ii) Services robotics.** These domains correspond to the experimental fields initiated in Grenoble (eMotion team) and in Lyon (CITI lab). However, the scientific objectives described in the previous sections are intended to apply equally to both applicative domains. Even our work on Bayesian Perception is today applied to the intelligent vehicle domain, we aim to generalize to any mobile robots. The same remark applies to the work on multi-agent decision making. We aim to apply algorithms to any fleet of mobile robots (service robots, connected vehicles, UAVs). This is the philosophy of the team since its creation.

Figure 4. Most of the Chroma platforms: the Pepper robot, a fleet of (22) Turtlebot 2, one of the 4 Bebop drones and the equipped Toyota Lexus.

4.2. 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

[24] see for instance the first International Workshop on Cloud and Robotics, 2016.

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 [25] 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).

Since about 8 years, we are collaborating with Toyota and with Renault-Nissan on these applications (bilateral contracts, PhD Theses, shared patents), but also recently with Volvo group (PhD thesis started in 2016). We are also strongly involved (since 2012) in the innovation project Perfect of the IRT [26] Nanoelec (transportation domain). In 2016, we have been awarded a European H2020 ECSEL project [27] 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 also with the Inria team TAMIS (Rennes). Chroma is also involved in the 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, see. Fig. 4 and Fig. 2), which are maintained by Inria-SED [28] and that allow the team to perform experiments in realistic traffic conditions (Urban, road and highway environments). The Zoe car will be automated in December 2016 through our collaboration with the team of P. Martinet (IRCCyN Lab, Nantes) that will open us to new experiments and work.

4.3. Services robotics

Service robotics is an application domain quickly 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, 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 (Turtlebot fleet) or aerial ones (ANR VIMAD [29]), see Fig. 4.

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 [30], we aim to propose smart technologies to assist electric wheelchair users in their displacements (see Figure 2 for illustration). 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 (Rennes).

Another emerging application to assist people is telepresence robot. In 2016 we started the TENSIVE project, funded by the Region, with the team of G. Bailly from GIPSA Lab (Grenoble) and with the Awabot and Hoomano companies (in Lyon). The project aims to improve the driving of such robots by providing a social and autonomous navigation (PhD of R. Cambuzat). Moreover, the project is supported by INSA-CITI Lab. through the acquisition of a Pepper robot (see Fig. 4).

[25] Advanced Driver Assistance Systems
[26] Institut de Recherche Technologique
[27] ENABLE-S3: European Initiative to Enable Validation for Highly Automated Safe and Secure Systems.
[28] Service Expérimentation et Développement
[29] Navigation autonome des drones aériens avec la fusion des données visuelles et inertielles, lead by A. Martinelli, Chroma.
[30] Personnaly assisted Living

5. Highlights of the Year

5.1. Highlights of the Year

- Laetitia Matignon, Associate Professor at Université de Lyon and LIRIS Lab has obtained an Inria delegation to join the Chroma team (half-time).
- Stephane d'Alu, research engineer at CITI lab., has joinded the team for one year, half-time.
- Christian Laugier is a co-author with A. Broggi, A. Zelinski and U. Ozguner, of the chapter "Intelligent Vehicles" of the 2nd edition of the "Hanbook of Robotics" edited by B. Sicilano and O. Khatib and published in July 2016.
- A new collaboration has been built with the team of Gabriella Czibula, from University of Babes-Bolyai in Cluj-Napoca, Romania. We obtained a bilateral french-romanian PHC project, called DRONEM, to support the collaboration for the period 2017-2018.
- A new collaboration has been built with the Volvo Group in Lyon, through the co-supervision of the PhD thesis of Guillaume Bono funded by the INSA-Volvo Chair.
- A new collaboration has been built with the GIPSA Lab in Grenoble and the team of Gerard Bailly (CNRS), through the co-supervision of the PhD thesis of Remi Cambuzat funded by the Region.
- The Chroma team has been reconducted for 2017 as a Nvidia CUDA lab, for his work related to "embedded perception and autonomous vehicles".
- A new Research contract on "robust sensor fusion involving vision data" has been signed with Toyota Motor Europe in 2016. The results have been patented by Inria and Toyota.
- The results obtained in the scope of the Research contract on "autonomous driving" have been patented by Inria, Insa and Toyota.
- Acquisition of a Pepper robot, funded by INSA de Lyon and CITI-Inria lab., and acquisition of 4 Crazyflies robots, funded by the CITI lab.

5.1.1. Awards

- Christian Laugier was awarded IROS Fellow at IROS 2016 and recieved the IROS Distinguished Award citation for his Outstanding Services to IROS Advisory/Steering Committee and IROS Conferences.

6. New Software and Platforms

6.1. CUDA-HSBOF

FUNCTIONAL DESCRIPTION

This software implements the HSBOF (Hybrid Sampling Bayesian Occupancy Filter) on GPU. It facilitates the integration of the model in an embedded chip.

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

6.2. DATMO (Detection and Tracking of Moving Objects)

FUNCTIONAL DESCRIPTION

This software is developped in the context of the autonomous driving assistance. It allows to detect, to track, and to classify mobile objects from LIDAR and mono-camera data. It can be linked or not with our previous implementation of the HSBOF software. The software is divided in 4 modules : Fusion, Detection, Tracking and Classification.

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

6.3. E.R.C.I.

Estimation of collision risks at road 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
FUNCTIONAL DESCRIPTION

This software is an implementation of the Occupancy Bayesian Filter (BOF) 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

Software in C++ for estimation based on the closed form solution

- Authors: Guillaume Fortier and Agostino Martinelli
- Contact: Agostino Martinelli

6.8. kinetics

FUNCTIONAL DESCRIPTION

Software computing decision support strategies and decision-making

- Contact: Jilles Dibangoye

7. New Results

7.1. Bayesian Perception

Participants: Christian Laugier, Lukas Rummelhard, Amaury Nègre [Gipsa Lab since June 2016], Jean-Alix David, Julia Chartre, Jerome Lussereau, Tiana Rakotovao, Nicolas Turro [SED], Jean-François Cuniberto [SED], Diego Puschini [CEA DACLE], Julien Mottin [CEA DACLE].

7.1.1. Conditional Monte Carlo Dense Occupancy Tracker (CMCDOT)

Participants: Lukas Rummelhard, Amaury Nègre, Christian Laugier.

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 and of the more recent developments done in 2015 in the scope of the Chroma team. This work exploits the *Bayesian Occupancy Filter (BOF)* paradigm [42], developed and patented by the team several years ago [31]. It also extends the more recent concept of *Hybrid Sampling BOF (HSBOF)* [76], whose purpose was to adapt the concept to highly dynamic scenes and to analyze 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 the period 2015-16 was to overcome some of the shortcomings of the initial *HSBOF* approach [32] , and to obtain a better understanding of the observed dynamic scenes through the introduction of an additional object level into the model. The new framework, whose development has been continued in 2016, is called *Conditional Monte Carlo Dense Occupancy Tracker (CMCDOT)* [84]. The whole CMCDOT framework and its results are presented and explained on a video posted on Youtube [33]. This work has mainly been performed in the scope of the project *Perfect* of IRT Nanoelec [34] (financially supported by the French ANR agency [35]), and also used in the scope of our long-term collaboration with Toyota.

In 2016, most of the efforts have been focused on the optimization of the implementation of our grid-based Bayesian filtering CMCDOT framework. Since the beginning of the development of this framework, we have chosen to construct models and algorithms specially designed to attain real-time performances on embedded devices, through a massively parallelization of the involved processes. The whole system have been implemented and scrupulously optimized in Cuda, in order to fully benefit from the Nvidia GPUs and technologies. Starting from the use of the Titan X and GTX980 GPUs (the hardware used in our computers and experimental platforms), we have successfully adapted and transferred our whole real-time perception chain on Nvidia dedicated-to-automotive cards Jetson K1 and X1 [36]. A specific optimization has been performed in term of data access and processing, allowing us to obtain real-time results when processing the data from the 8 lidar layers generated by our IBEO sensors, by using a grid containing 1400x600 cells and 65536 dynamic particles (for motion estimation). The observation grid generation and fusion (representing the input of the CMCDOT) is made in 17ms on Jetson K1 and only in 0.7ms on Jetson X1; a CMCDOT filtering update is performed in 70ms on Jetson K1 and only in 17ms on Jetson X1.

[31] The *Bayesian programming formalism* developed in e-Motion, pioneered (together with the contemporary work of Thrun, Burgards and Fox [94]) a systematic effort to formalize robotics problems under Probability theory –an approach that is now pervasive in Robotics.

[32] 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 [47], [85], etc), the retrospective object level analysis by dynamic grid segmentation can be computationally expensive and subjected to some data association errors.

[33] https://www.youtube.com/watch?v=uwIrk1TLFiM

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

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

[36] These new Nvidia devices are more suited for embedded applications, in term of power consumption and dimensions.

Figure 5. Jetson X1 card, Nvidia device dedicated to automotive applications

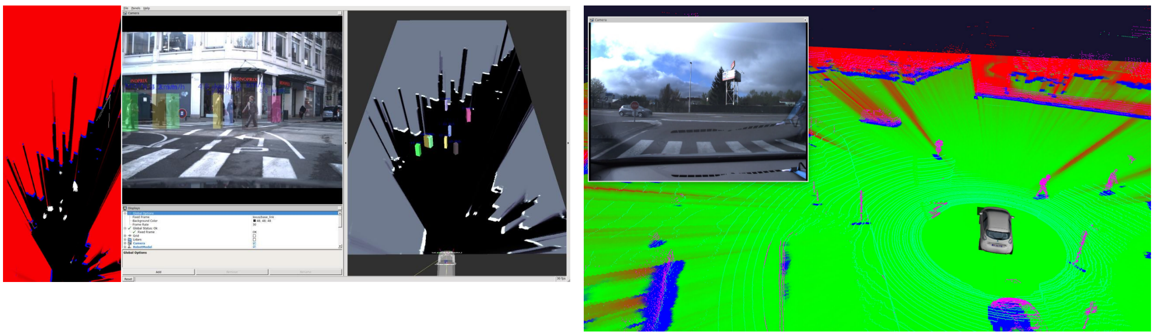

Figure 6. a) CMCDOT results : filtered occupancy grids, enhanced with motion estimations (vectors) and object detection (colored boxes) b) Example of an occupancy grid generated using the classified point cloud and the ground model

7.1.2. A new sensor model for 3D sensors, by Ground Estimation, Data segmentation and adapted Occupancy Grid construction

Participants: Lukas Rummelhard, Amaury Nègre, Anshul Paigwar, Christian Laugier.

As a starting point for the Bayesian perception framework embedded on the vehicles and on the perception boxes, the system generates instantaneous spatial occupancy grids, by interpreting the point clouds generated by the sensors (sensor model). With planar sensors, placed at the level of the wanted occupancy grid, such as the IBEO Lidar on the vehicles or the Hokuyo Lidar on the first developed perception box, a classic sensor model can be used: before the laser impact the space is considered as empty, occupied at the impact point and undefined after the impact. In our previous approach, the angular differences between the 4 laser layers of our IBEO Lidars was taken into account by introducing a *confidence factor* in the data, reducing in this way the effect of the impacts too close to the ground. In this approach the ground is assumed to be flat and the confidence factor is calculated geometrically. Then, given the orientation of these sensors and the environments traversed, such a model was quite satisfactory.

However, this traditional sensor model has to be adapted when using Velodyne or Quanergy sensors mounted on the top of the vehicle and providing dense 3D data with a high horizontal and vertical resolution. Indeed, in this case the laser layers are capable of depicting an obstacle from above, and consequently an impact at a given distance does not certify any more a free area until the impact. Moreover, many impact points are located on the ground and have to be appropriately modeled in order to systematically avoid deceptive obstacle detection. Then, the previous flat-ground assumption doesn't hold anymore, since the actual ground shape is integrated into the data and the correct segmentation of obstacle becomes critical in the process. This is why we have developed the new *Ground Estimator* approach.

The aim of the method is, upstream from the Bayesian filtering step of our current perception system (CMCDOT), to first dynamically *estimate the ground elevation*, to exploit this information for making a *relevant data classification* between actual obstacle impacts and ground impacts, and finally to generate the *relevant occupancy grid using this classified 3D point cloud* (sensor model). The developed method is based on a recursive spatial and temporal filtering of a Bayesian network of elevation nodes, constantly re-estimated and re-evaluated with respect to data and spatial continuity. The construction of the occupancy grid is based, on the one hand, on the location of the laser impacts, and on the other hand on the shape of the ground and the height at which the lasers pass through the different portions of the space.

The approach has been first successfully tested and validated with dense Lidar sensors (Velodyne and Quanergy). The use of the enhanced sensor model is also currently tested with sparser sensors, with the objective to increase their robustness. The obtained results show promising perspectives, offering a robust and efficient ground representation, data segmentation and relevant occupancy grid, and also offering quality inputs for the next steps of the perception framework. A journal paper and a patent are under preparation.

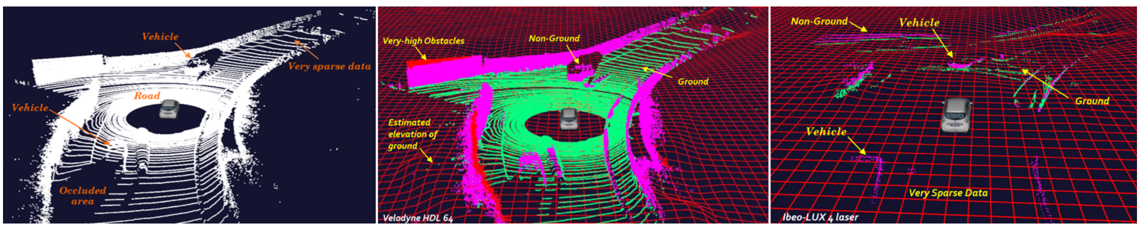

Figure 7. (a) Typical 3D point cloud generated by Velodyne LiDAR, (b) Point cloud segmentation between ground (green points) and non-ground (purple points), and estimated average elevation of the terrain (red grid) (c) Point Cloud Segmentation on 4-Ibeo Lux LiDAR data and estimated elevation of terrain.

7.1.3. Dense & Robust outdoor perception for autonomous vehicles

Participants: Victor Romero-Cano, Christian Laugier.

Robust perception plays a crucial role in the development of autonomous vehicles. While perception in normal and constant environmental conditions has reached a plateau, robust perception in changing and challenging environments has become an active research topic, particularly due to the safety concerns raised by the introduction of self-driving cars to public streets. In collaboration with Toyota Motors Europe and starting in April 2016 we have developed techniques that tackle the robust-perception problem by combining multiple complementary sensor modalities.

Our techniques, similar to those presented in [78], [91] explore the complementary relationships between passive and active sensors at the pixel level. Low-level sensor fusion allows for an effective use of raw data in the fusion process and encourages the development of recognition systems that work directly on multi-modal data rather than higher level estimates. During the last nine months we have developed low-level sensor fusion approaches that, differently from most of the related literature, do not have fixed requirements regarding coverage or density of the active sensors. This provides a competitive advantage due to the elevated costs of dense range sensors such as Velodyne LIDARs.

Our framework outputs a new image-like data representation where each pixel contains not only colour but also other low level features such as depth and regions of interest where generic objects are likely to be. Our approach is generic so it allows for the integration of data coming from any active sensor into the image space. Additionally, it does not aim at tackling the object detection problem directly but it proposes a multi-modal-data representation from which object detection methods may benefit. For evaluation purposes we have tackled the concrete problem of fusing color images and sparse lidar returns, however, as explained before, the framework is amenable for the inclusion of any other range-sensor modality. The framework creates *XDimages* by extrapolating range measurements across the image space in a two-stage procedure. The first stage considers locally homogeneous areas given by a super-pixel segmentation while the second one further expands depth values by performing self-supervised segmentation of areas seeded by the range sensor. The framework's pipeline is illustrated in Figure 8.

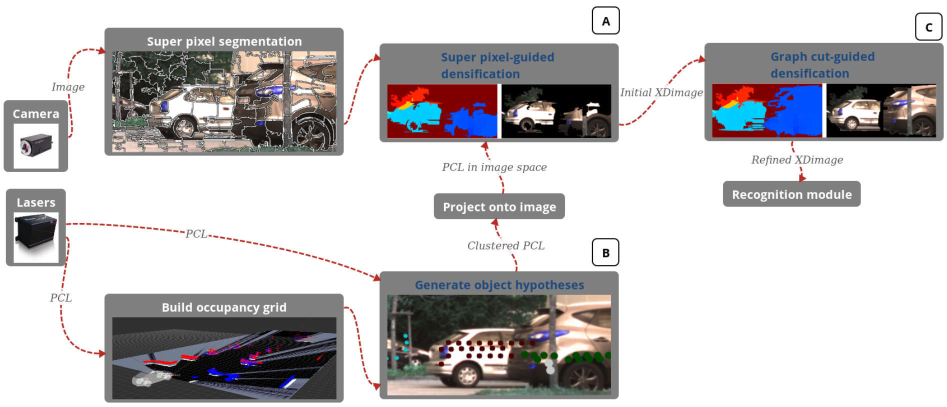

Figure 8. The XDvision framework.

We have named an instance of our data structure an *XDimage*. It corresponds to an augmented camera image where individual pixels contain both appearance and geometric information. The first and more challenging problem to be solved in order to build XDimages is that of densifying sparse point cloud data provided by active range sensors. In our approach we extrapolated depth information using a two-steps procedure as follows:

1. Extend depth values projected onto individual pixels to neighbouring pixels that have similar appearance.
2. Obtain geometry-based object hypothesis.
3. For each geometry-based object hypothesis, extrapolate range measurements in order to account for entire objects.

The results of this work have resulted in a patent application [82] and a paper submission to ICRA 2017 [83].

7.1.4. Integration of Bayesian Perception System on Embedded Platforms

Participants: Tiana Rakotovao, Christian Laugier, Diego Puschini [CEA DACLE], Julien Mottin [CEA DACLE].

Perception is a primary task for an autonomous car where safety is of utmost importance. A perception system builds a model of the driving environment by fusing measurements from multiple perceptual sensors including LIDARs, radars, vision sensors, etc. The fusion based on occupancy grids builds a probabilistic environment model by taking into account sensor uncertainties. Our objective is to integrate the computation of occupancy grids into embedded low-cost and low-power platforms. Occupancy Grids perform though intensive probability calculus that can be hardly processed in real-time on embedded hardware.

As a solution, we introduced a new sensor fusion framework called *Integer Occupancy Grid* [80]. Integer Occupancy Grids rely on a proven mathematical foundation that enables to process probabilistic fusion through simple addition of integers. The hardware/software integration of integer occupancy grids is safe and reliable. The involved numerical errors are bounded and parameterized by the user. Integer Occupancy Grids enable a real-time computation of multi-sensor fusion on embedded low-cost and low-power processing platforms dedicated for automotive applications. This research work has been conducted in the scope of the PhD thesis of Tiana Rakotovao, which will be defended in February 2017.

Figure 9. Fusion of three front LIDARs and one rear LIDAR on the ZOE platform

Experiences showed that Integer Occupancy Grids enable the real-time fusion of the four ibeo LUX LIDARs mounted on the ZOE experimental platform of IRT Nano-Elec [79]. The LIDARs produces about 80,000 points at 25Hz. These points are fused in real-time through a hardware/software integration of the Integer Occupancy Grid framework on an embedded CPU based on ARM A9@1GHz. The platform respects the low-cost and low-power constraints of processing hardware used for automotive. The fusion produces an occupancy grid at more than 25 Hz as illustrated on figure 9.

7.1.5. Embedded and Distributed Perception

Participants: Christian Laugier, Julia Chartes, Amaury Nègre, Lukas Rummelhard, Jean-Alix David, Jerome Lussereau, Nicolas Turro [SED], Jean-Francçois Cuniberto [SED].

7.1.5.1. Embedded Perception in an Experimental Vehicle Renault ZOE

In the scope of the *Perfect* project of the IRT nanoelec, we have started to build an experimental platform using a Renault Zoe equipped with several types of sensors (see 2014 and 2015 annual activity reports). The platform includes multiple sensors, an embedded perception system based on the CMCDOT, and a collision risk component, figure 10(a) illustrates.

Figure 10. (a) Display of the HMI (b) Collision simulation with a mannequin (c) On left: picture of the smartbox, on right: picture of the cone.

In 2016, we have continued to develop and to improve the platform using the latest version of the CMCDOT, some optimized perception and localization components, and new V2X communication functions for distributed perception.

In particular, we have developed an improved the localization function using maps and V2X communication devices. We also developed a new embedded component for sharing data between the infrastructure perception boxes and the vehicle; this component is based on the use of V2X communication and GPS time synchronization. This is a first step towards a fully distributed perception system. The development of this system will be continued in 2017 (see next section).

During the year 2016, experiments have been pushed forward on testing the perception algorithms, the collision risk alert and the localization components using a fabric mannequin as shown on figure 10(b). The mannequin has been motorized for easier and more realistic tests and demos. More details are given in the team publications at MCG 2016 [29] and at GTC Europe 2016. The work of the team is also explained on youtube videos "Irt Nanoelec Perfect Project" [55] and for the technical side "Bayesian Embedded Perception" [54].

New experiments have also been performed on some road intersections and highways, in order to collect new data on driver's behaviors. These experiments have been conducted on mountain roads with changing slopes and on highway (to study the lane changing behaviors). They have been performed in the scope of our cooperation with Renault and with Toyota. The way these experimental data have been used is described in the section “Situation Awareness”. More recently, we have also started to work on the development of the automatic driving controls on the Zoe vehicle. For that purpose, we have recently signed a cooperation agreement with Ecole Centrale de Nantes. The basic functions for automatic driving will be implemented on the Zoe at the beginning of 2017. For that purpose, a physical model of the Zoe is currently in construction under ROS Gazebo simulator. This should allow us to implement and to test the required control laws.

7.1.5.2. Distributed Perception

In 2015, we have developed a first *Connected Perception Box* including a GPS, a V2X communication device, a cheap Lidar sensor, and an Nvidia Tegra K1 board. The box was powered using a battery, and the objective was to reduce as far as possible the required energy consumption. Within the box, the perception process is performed using the CMCDOT algorithm. In 2016, we have continued to develop this concept of distributed perception. We have developed a second generation of the perception box, using a Quanergy M8 360° Lidar, a TX1 Nvidia Tegra board, an ITRI V2X communication device and the last version of the CMCDOT system. This new box is more efficient and powerful than the previous one. It allows the real-time exchange of objects positions and velocities, through a V2X communication between the perception box and the connected vehicle. This leads to the extension of the vehicle perception area to some hidden areas, and to generate some alerts in case of a high collision risk, cf. fig. 11. In this approach, time synchronization has been performed using GPS time and NTP protocol.

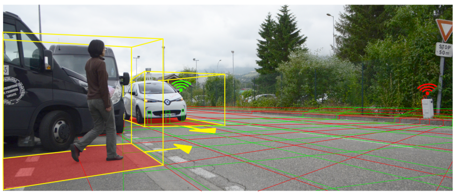

Figure 11. (a) Shared perception between car and perception box

7.1.5.3. Public demonstrations and Technological Transfer

2016 has been a year with many scientific events and public demos. Several public demonstrations of our experimental vehicle have performed, some of them in presence of local government officials during a GIANT show at CEA.

The collaboration with Nvidia on Embedded Perception for autonomous driving has been extended to 2017, and the "GPU research center" label has been renewed.

Toyota Motor Europe (TME) is strongly interested in the CMCDOT technology, and Inria is currently negotiating with them the conditions of a first licence for R&D purpose. A first implementation of the executable code of CMCDOT has successfully been implemented on the TME experimental vehicle in Brussels. We are currently discussing with TME an extension of the license to several other experimental vehicles located in some other places in the world.

At the end of 2016, we also started to transfer the CMCDOT technology to two industrial companies in the fields of industrial mobile robots and automatic shuttles. Confidential contracts for the joint development of proofs of concepts are under signing. The work will be performed at the beginning of 2017.

7.2. Situation Awareness

Participants: Christian Laugier, Olivier Simonin, Jilles Dibangoye, Alejandro Dizan Vasquez Govea [Apple since January 2016], Stephanie Lefevre [Mercedes-Benz North America], David Sierra-Gonzalez, Mathieu Barbier, Victor Romero-Cano.

7.2.1. Framework for Motion Prediction and Collision Risk Assessment

Participants: Christian Laugier, Alejandro Dizan Vasquez Govea [Apple since January 2016], Stephanie Lefevre [Mercedes-Benz North America], Lukas Rummelhard.

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 and Chroma team 2015 activity report).

Throughout 2016, we have continued this line of work by developing and experimentally testing new frameworks for Motion Prediction and Collision Risk Assessment in complex dynamic scenes involving multiple moving agents having various behaviors. This work has been conducted in the scope of three main scenarios: Short-term prediction in crowded urban environments (see approach and results in sections 7.1.1 and 7.1.5), Autonomous driving in highway environments (see section 7.2.2), and Safe Intersection crossing.

The main underlying concepts of the developed framework have recently been published in the second edition of the Handbook of Robotics [31]. They have also been presented into a Mooc course on “Autonomous Mobiles Robots and Vehicles”, dedicated to graduate and undergraduate students and to engineers in Robotics [57]. This Mooc has been published twice in 2015 and in 2016.

The recent results have been published at ICRA 2016 [27] and also presented by C. Laugier in several invited talks : Asprom2016 [16], ICIT2016 [14], CUHK2016 [15], GTC-Europe2016 [24] and ARSO2016 [17].

Another contribution relies in the implementation of some the proposed models on two experimental vehicles (Lexus and Zoe experimental platforms). As it has been mentioned in the section 7.1.5, several experiments on short-term collision risk assessment have successfully been conducted with these platforms in 2015 and 2016 (c.f. [84], [67]).

This work will be continued in 2017, in the scope of our ongoing collaborative projects with Toyota, Renault and IRT nanoelec. It will also be used as a support for the planned technological transfers with two industrial companies in the fields of industrial mobile robots and automatic shuttles (see section 7.1.5).

7.2.2. Planning-based motion prediction for collision risk estimation in autonomous driving scenarios

Participants: David Sierra-Gonzalez, Christian Laugier, Jilles Dibangoye, Alejandro Dizan Vasquez Govea [Apple since January 2016].

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-Gonzáles.

One key factor, and probably the biggest challenge in order to produce robust collision risk estimation in traffic scenes, is the motion prediction of the dynamic obstacles (i.e. the other drivers for highway scenarios). The difficulty stems from the fact that human behavior is determined by a complex set of interdependent factors, which are very hard to model (e.g. intentions, perception, emotions). As a consequence, most existing systems are based on simple short-term motion models assuming constant velocity or acceleration.

We opt here for a planning-based approach, which assumes that drivers instinctively act as to minimize a cost (or equivalently, maximize a reward). This cost 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. By using Inverse Reinforcement Learning (IRL) algorithms, we can obtain such cost function directly from expert demonstrations (i.e. simply observing how people drive).

Two well-known IRL algorithms [35], [101] have been implemented and used to obtain driver models from human demonstrations. The algorithms have been adapted to work with simulated demonstrations obtained on a highway simulator, and with real-world data from the Lexus and Renault Zoe platforms. Figure 12.a shows a slice of one such cost function in the context of a real highway scene.

A novel framework has been developed in order to exploit the predictive potential of these models for the task of highway scene prediction [26]. The ability of these dynamic models to capture the risk-aversive behavior of drivers leads to an interaction-aware prediction. In contrast to other state-of-the-art interaction-aware approaches [59], the complexity of our prediction framework does not grow exponentially in the number of vehicles in the scene, but only quadratically. Figure 12.b shows the prediction produced by our framework in two prototypical simulated highway scenarios. The figure shows the result of summing up across the occupancy distributions over a discretization of the road for all the vehicles in the scene, at different timesteps (note that the result is no longer a probability distribution, but it is convenient to visualize the prediction).

This framework has been patented by Inria and Toyota Motor Europe in October 2016.

7.2.3. Functional space representation for automated road intersection crossing

Participants: Mathieu Barbier, Christian Laugier, Olivier Simonin.

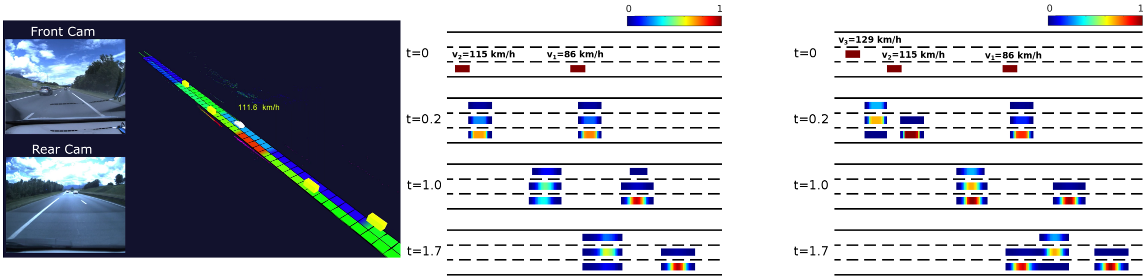

Figure 12. a) Slice of a cost function obtained from real demonstrated data superimposed on the road on a highway scene. Red indicates high cost, green intermediate, and blue low. b) and c) Prediction of two prototypical simulated traffic scenes with the framework from [26]. We show the predicted occupancy probabilities over a discretization of the road for different timesteps.

The objective is to develop a framework for modeling road intersections using relevant functional areas, which can be exploited by an autonomous vehicle for safely crossing the intersection. These functional areas try to capture various characteristics such as crossing, merging or approaching areas, the car dynamics when moving in such areas, or the related uncertainty. We made the assumption that such a functional space representation can be stored in a map and can be constructed using observed trajectories. This work is performed in the scope of the PhD thesis of Mathieu Barbier, which is supported by a CIFRE fellowship with Renault.

In a preliminary work done with map by Renault, it has been observed that the information stored in a map does not fully match with the real motions executed by cars within a given intersection. The differences between the stored and the real path might be important. This difference is not due to error during the map creation, but rather to other constraints related to the driving action (e.g. visibility, dynamics). Such a difference leads to serious difficulties at the level of the autonomous driving decision-making process.

Constructing a functional model, requires to first analyze the topological and dynamics structure of an intersection, and in a second step to imagine how it would be possible to extract such type of information from maps and observed trajectories. Two main structures seem to emerge from this study:

- Merging and Crossing points, areas where two cars are the most likely to collide.
- Approaching areas, areas where drivers are most likely to show constant driving behaviors.

In order to learn motions patterns of multiple cars, we have chosen to train Gaussian processes [81] [93] using simulated data set generated using the SCANER™system. The resulting distribution is segmented using different threshold, in order to find approaching areas and to combine pairs of such areas for constructing overlapping areas. The correlation between this discretization and both real and simulated velocity profiles has been shown by the experimental results, see Fig. 13. The approach has been published at IEEE ITSC 2016 [18].

We recently started to make use of a Random Forest classifier to connect features of trajectories with an intended maneuver (stop, pass, yield) and to take advantage of the discretization. This research work will be continued in 2017.

7.3. Robust state estimation (Sensor fusion)

7.3.1. Visual-inertial structure from motion: observability properties and state estimation

Participant: Agostino Martinelli.

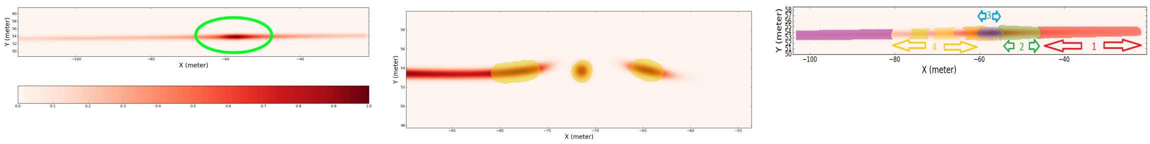

Figure 13. Different step of the framework to discretize the space : a) Map created with prediction from set of GPs, the highlighted area has a high mean probability b) Segmentation of crossing and merging areas, in red the probability of two cars being in the same position and in yellow where this probability is higher than the threshold c) Discretization of approaching area

This research is the follow up of our investigations carried out during the last three years. The main results obtained this year regard the following three topics:

1. Exploitation of the closed form solution introduced in [70] in the framework of Micro Aerial Vehicle (MAV) navigation;
2. Introduction of a new method for simultaneous localization and Gyroscope calibration;
3. Analytic solution of the Unknown Input Observability problem (UIO problem) in the nonlinear case.

Regarding the first two topics, we successfully implemented a new method for MAV localization and mapping, on the aerial vehicles available at the Vision and Perception lab at the university of Zurich [37]. This method is based on our previous closed form solution recently introduced in [70]. The practical advantage of this solution is that it is able to determine several physical quantities (e.g, speed, orientation, absolute scale) by only using the measurements provided by a monocular camera and an Inertial Measurement Unit (IMU) during a short interval of time (about 3 seconds). In other words, an initialization is not requested to determine the aforementioned physical quantities. This fact has a fundamental importance in robotics and it is novel with respect to all the state of the art approaches for visual-inertial sensor fusion, which 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.

Finally, by further studying the impact of noisy sensors on the performance of the closed-form solution introduced in [70], we found that this performance is very sensitive to the gyroscope bias. For, we developed a powerful and simple optimization approach to remove this bias. This method has been tested in collaboration with the vision and perception team in Zurich (in the framework of the ANR-VIMAD) and published on the IEEE Robotics and Automation Letters [12]. Additionally, these results have been presented at the International Conference on Robotics and Automation [21].

Regarding the third topic, we still considered the problem of deriving the observability properties of the visual-inertial structure from motion problem when the number of inertial sensors is reduced. This case corresponds to solve a problem that in control theory is known as the Unknown Input Observability (UIO). This problem was still unsolved in the nonlinear case. In [71] 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 [71] 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. Our effort to deal with this fundamental issue, was devoted to separate the information on the original state from the information on its extension. Last year, we fully solved this problem in the case of a single unknown input [73], [72]. This year we solved the problem for any number of unknown inputs. We presented this solution at the university of Pisa in June and at the university of Rome, Tor Vergata, in December.

[37] This is the partner of the ANR project VIMAD, in charge of the experiments

7.4. Motion-planning in human-populated environment

We explore motion planning algorithms to allow robots/vehicles to navigate in human populated environment, and to predict human motions.

We have proposed a novel planning-based motion prediction approach [27] which addresses the weaknesses of the previous state-of-the-art motion prediction technique [56], namely *High computational complexity* and *Limited ability to model the temporal evolution along the predicted path*. In 2016, this work has evolved in two new directions, which are prediction of pedestrian behaviors in urban environments and mapping of human flows. We also started to investigate the navigation of a telepresence robot in collaboration with the GIPSA Lab. These work are presented here after.

7.4.1. Urban Behavioral Modeling

Participants: Pavan Vasishta, Raphael Frisch, Anne Spalanzani.

The objective of modeling urban behavior is to predict the trajectories of pedestrians in towns and around car or platoons. We aim to integrate various entities of urban environments such as crosswalks, sidwalks, points of interest, but also characteristics of mobile obstacles (such cars and platoons) and proxemics in order to build a costmap that will show how pedestrians are driven around the ego-vehicle. This work is in the scope of the VALET project and the PhD of Pavan Vasishta (in collaboration with the Inria team Pervasive Interaction). It started in february 2016. Furthermore, a collaboration with the Laboratory of Psychology and NeuroCognition of Grenoble has been initiated to ground interaction and personal space models in experimental data from psychology.

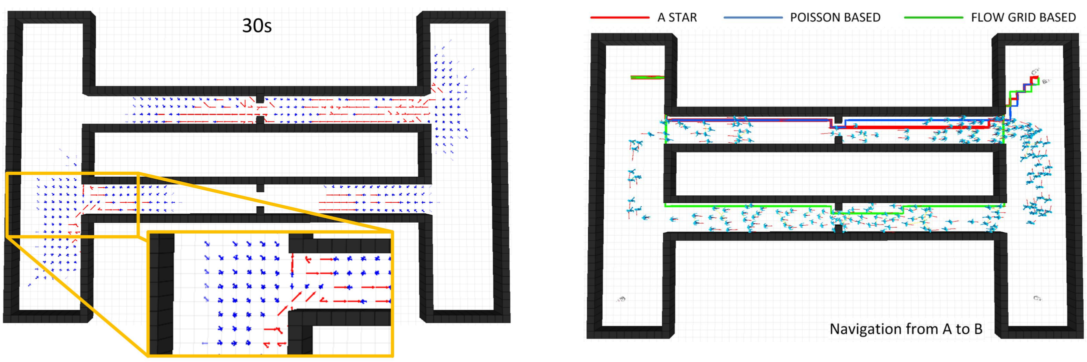

Figure 14. Illustration of (a) Flow-grid mapping in a two-corridor environment where 200 moving pedestrians turns (b) A path-planning computed with different cost functions in this populated environment*

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

Participants: Olivier Simonin, Jacques Saraydaryan, Fabrice Jumel.

In order to deal with robot navigation in dense human populated environments, eg. in flows of humans, we started to investigate the problem of mapping these flows. The challenge is to build such a map from robot perceptions while robots move autonomously to perform some tasks. We developped a counting-based grid model which computes likelihoods of human presence and motion direction in each cell, see red vectors in Fig. 14.a (this is a statistical learning of repetitive human motions). We extended the flow grid model with a human motion predictive model based on the Von Misses motion patern, allowing to "accelerate" the flow grid mapping, see blue vectors in Fig. 14.a.

Then we explored how path-planning can benefit of such a flow grid, that is taking into account the risk for a robot to encounter humans in opposite direction. We first implement the Flow-Grid model in a simulator built upon PedSim and ROS tools, allowing to simulate mobile robots, crowd of pedestrians and sensors to detect their motion. Then, we compared three A*-based path-planning models using different levels of information about human presence: non-informed, a grid of human presence likelihood proposed by Tiplaldi [95] and our grid of human motion likelihood. Simulations involving 200 moving persons and 4 collaborative robots allowed to test simultaneously the mapping of human motions and the related path-planning. The different kind of paths obtained are illustrated in Fig. 14.b, showing the ability of the flow-grid based A* to avoid to cross areas with a possible opposite human flow. These results have been presented at RSS workshop DEMUR [30].

We also started some experiments with our mobile indoor robots (incl. the Pepper) in human populated environments, see [30]. We plan to demonstrate the efficiency of the approach by participating to the new Pepper-league of the Robocup@Home competition, over the future period 2017-2020.

7.4.3. Navigation of telepresence robots

Participants: Olivier Simonin, Anne Spalanzani, Gerard Bailly [GIPSA, CNRS, Grenoble], Rémi Cambuzat.

In 2016 we obtained with the team of Gérard Bailly, from GIPSA/CNRS Grenoble, a regional support for the TENSIVE project. It funds the PhD thesis of Remi Cambuzat on immersive teleoperation of telepresence robots for verbal interaction and social navigation, started in October 2016. Chroma is focusing on the problem of social navigation, and more paricularly on the balance between human commands and autonomous navigation. Two issues are adressed : how to understand the expected direction given by the pilot to the teleprence robot, in order to ease the workload of the pilot ? how to assist the navigation, from embedded processes and sensors on the robot, while following the expected behavior given by the remote pilot ?

First months of the thesis concerned the building of a specific state-of-the-art, the formalization of some experimental scenarios, and the study of the Pepper robot capabilities in this scientific challenge.

7.5. Decision Making in Multi-Robot Systems

7.5.1. Multi-robot path-planning and patrolling

7.5.1.1. Patrolling under connectivity constraints

Participants: Olivier Simonin, Anne Spalanzani, Mihai Popescu, Fabrice Valois [Inria, Agora (ex Urbanet) team].

Patrolling is mainly used in situations where the need of repeatedly visiting certain places is critical. In this work, we consider a deployment of fixed targets, eg. wireless sensors, that several robots are in charge of patrolling while they have to maintain their (periodic) connectivity in order to collect and bring data up to a sink node. We have shown that this is fundamentally a problem of vertex coverage with bounded simple cycles (CBSC). We offered a formalization of the CBSC problem and proved it is NP-hard and at least as hard as the Traveling Salesman Problem (TSP). Then, we provided and analyzed heuristics relying on clusterings and geometric techniques. The proposed approach relies on two steps: the first one partitions the vertices, the second one computes hamiltonian cycles on each partition. We implemented two classic hamiltonian cycle heuristics, one is based on Minimum Spanning Trees computations and the other on Christofides algorithm. Comparisons on randomly-generated graphs showed that the Christofides algorithm computes shorter cycles. This work, started in the Master internship of Mihai-Ioan Popescu, now continuing as PhD student in Chroma, has been published in 2016 in [25]. Work is now focusing on the problem of synchronizing robots to meet at intersection nodes between the cycles.

Another important element of this work is the construction of a new collaboration with the team of Gabriela Czibula in Babes-Bolyai University at Cluj-Napoca (Romania). It will focus on optimization and online adaptation of the multi-cycle patrolling with machine learning (RL) techniques in order to deal with the arrival of new targets in the environment. We obtained, in the end of 2016, a french-romanian PHC [38] bilateral project, called DRONEM, funding students and researchers exchanges during two years.

[38] Hubert Curien Partnership

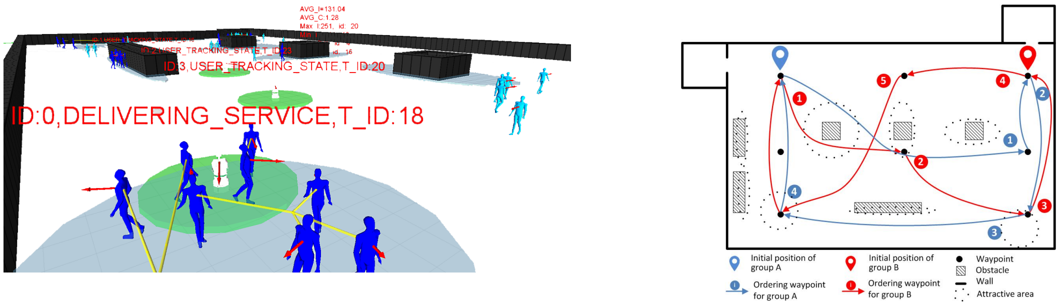

Figure 15. a) Simulator for dynamic patroling of people based on PedSim. b) Scenario of the 200 pedestrians moving along two predefined paths plus local attractors and randoms moves.

7.5.1.2. Patrolling moving people (dynamic patrolling)

Participants: Jacques Saraydaryan, Fabrice Jumel, Olivier Simonin.

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 showed that the problem can be formally expressed as a dynamic patrolling task. We call it the robot-waiters problem, where robots have to regularly visit all the moving persons (to deliver objects/information). In the publication [87], 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 particular greedy-based solutions on distance and idleness people information. 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 evaluated performances by using our simulator (combining PedSim and ROS). The simulator and the scenrio test - paths followed by humans - are illustrated in figure 15.a and 15.b. Experimental results show the efficiency of the specific new approaches over standard (static patrolling) approaches. We also analysed the influence of the number of robots on the performances, showing a convergence of performances when it grows. See [87] and extensions in 2016 [28].

We are currently developping new algorithms using the mapping and prediction of human flows based on the work presented in section 7.4.2 to allow robots to predict where human (groups) will move (under hypothesis of repetitive behaviors).

7.5.1.3. Global-local optimization in autonomous multi-vehicles systems

Participants: Olivier Simonin, Jilles Dibangoye, Laetitia Matignon, Florian Peyreron [VOLVO Group, Lyon], Guillaume Bono, Olivier Buffet [Inria Nancy Grand Est], Mohamed Tlig [IRT-Systemx, Paris].

We address transport and traffic management problems with driverless vehicles. We mainly study how local decisions can improve complexity of global (planning) solutions.

A previous work carried in the PhD of M. Tlig [96] concerned stop-free crossing roads with driverless vehicles. We explored distributed algorithms to optimize the global traffic in the road network (time and energy), based on Hill-Climbing techniques, so as to go from a synchronization within each intersection to the synchronization of a network. Experiments in simulation showed that proposed algorithms can efficiently optimize the initial decentralized solution, while keeping its properties (only the temporal phase for crossing in each intersection is modified). In 2016 we extended the experimental study, which was published in the RIA revue [13] and submited to an international journal.

In 2016, we started a new cooperation with the VOLVO Group, in the context of the INSA-VOLVO Chair. It funds the PhD thesis of G. Bono which deals with global-local optimization under uncertainty for goods distribution using a fleet of autonomous vehicles. First months of the thesis focused on building i) a state of the art about online pick-up and delivery solutions with a fleet of autonomous vehicles and ii) defining formally the scenario and hypothesis of the considered problem.

7.5.2. Anytime algorithms for multi-robot cooperation

7.5.2.1. Complex scenes observation

Participants: Olivier Simonin, Laetitia Matignon, Christian Wolf [LIRIS, INSA Lyon], Simon Bultmann [internship], Stefan Chitic.

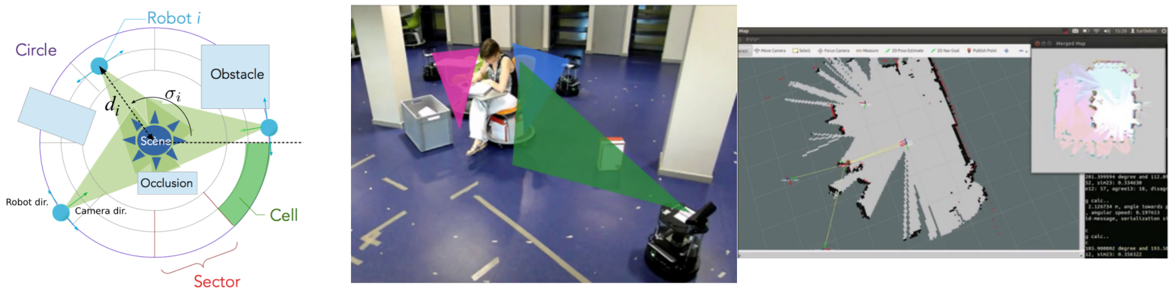

Figure 16. Illustrations (a) Concentric navigation model. (b) Experimental setup and multi-robot mapping with Turtlebot 2.

Solving complex tasks with a fleet of robots requires to develop general 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 "Crome" [39] project [40] is motivated by 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 localization.

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. 16.a). This model is combined with an incremental mapping of the environment and exploration guided by meta-heuristics in order to limit the complexity of the exploration state space. We developped a simulator that uses real data from real human pose captures to simulate dynamic scene and noise in sensor information. A video presenting the simulator interface and showing the incremental exploration and mapping can be found at . Results have been published in 2016 in [20] (ICTAI). It compares the variants of the approach and shows its features such as adaptation to the dynamic of the scene and robustness to the noise in the observations.

We have also developped an experimental framework for the circular navigation of several Turtlebot2 robots around a scene, presented in figure 16.b. Especially, given that we assume in our work that robots have no map of the environment, we implemented a cooperative multi-robot mapping based on the merging of occupancy grid maps. Robots are individually building and communicating to other robots their local maps. Each robot tries to align these local maps to compute a joint, global representation of the environment. We carried out

[39]Coordination d'une flottille de robots mobiles pour l'analyse multi-vue de scènes complexes
[40]Funded by an INSA BQR in 2014-2015 (led by O. Simonin) and a LIRIS transversal project in 2016-2017 (led by L. Matignon)

the map-merging by adapting several methods known in literature [86] to our specific topology, i.e. the single hypothesis of a common center point (the scene) shared by robots. We compared the methods in real-world multi-robot scenarios (see Simon Bultmann's internship report).

7.5.2.2. Middleware for open multi-robot systems

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 the context of the PhD work of S. Chitic, we address 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 pubished in [19]. In 2016, the work continued by the definition of a timed automata based design and validation tool-set, that offers a framewok to formalize and implement multi-robot behaviors and to check some (temporal) properties.

7.5.3. Sequential decision-making under uncertainty

The holy grail of Artificial Intelligence (AI)—creating an agent (e.g., software, robot or machine) that comes close to mimicking and (possibly) exceeding human intelligence—remains far off. But past years have seen breakthroughs in agents that can gain abilities from experience with the environment, providing significant advances in the society and the industries including: health care, autonomous driving, recommender systems, etc. These advances are partly due to single-agent planning and (deep) reinforcement learning, that is, AI research subfields in which the agent can describe its world as a Markov decision process. Some stand-alone planning and reinforcement learning (RL) algorithms (e.g., Policy and Value Iteration, Q-learning) are guaranteed to converge to the optimal behavior, as long as the environment the agent is experiencing is Markovian. Although Markov decision processes provide a solid mathematical framework for single-agent planning and RL, they do not offer the same theoretical grounding in multi-agent systems, that is, groups of autonomous, interacting agents sharing a common environment, which they perceive through sensors and upon which they act with actuators. Multi-agent systems are finding applications everywhere today. At home, in cities, and almost everywhere, we are surrounded by a growing number of sensing and acting machines, sometimes visibly (e.g., robots, drones, cars, power generators) but often imperceptibly (e.g., smartphones, televisions, vacuum cleaners, wash- ing machines). Before long, through the emergence of a new generation of communication networks, most of these machines will be interacting with one another through the internet of things. In contrast to single-agent systems, when multiple agents interact with one another, how the environment evolves depends not only upon the action of one agent but also on the actions taken by the other agents, rendering the Markov property invalid since the environment is no longer stationary. In addition, a centralized (single-agent) control authority is often inadequate, because agents cannot (e.g., due to communication cost, latency or noise) or do not want (e.g., in competitive or strategic settings) to share all their information all the time. This raises a simple fundamental question: how to design a general algorithm for efficiently computing rational policies for a group of cooperating or competing agents in spite of stochasticity, limited information and computational resources? The remainder of this section points out some of the main results of the year to this question as well as ongoing projects.

7.5.3.1. Optimally solving cooperative games as continuous Markov decision processes

Participants: Jilles S. Dibangoye, Olivier Buffet [Inria Nancy], Christopher Amato [Univ. New Hampshire], François Charpillet [Inria Nancy, Larsen team].

Decentralized partially observable Markov decision processes (Dec-POMDPs) provide a general model for decision-making under uncertainty in decentralized settings, but are difficult to solve optimally (NEXP-Complete). As a new way of solving these problems, we introduce 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, 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. 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 demonstrating that our approach provides significant scalability improvements compared to the state of the art. This work has been published in JAIR journal [11].

7.5.3.2. Optimally solving two-person zero-sum partially observable stochastic games: a convex optimization approach

Participants: Jilles S. Dibangoye, Olivier Buffet [Inria Nancy], Mihai Indricean [INSA Lyon internship].

This work proposes a novel theory and algorithms to optimally solving a two-person zero-sum POSGs (zs-POSGs). That is a general framework for modeling and solving two-person zero-sum games (zs-Games) with imperfect information. Our theory builds upon the result demonstrating that the original problem is reducible to a zs-Game—but now with perfect information. In this form, we show that the dynamic programming theory applies. In particular, we extended Bellman equations [39] for zs-POSGs, and coined them maximin (resp. minimax) equations. Even more importantly, we demonstrated Von Neumann & Morgenstern's minimax theorem [99] [100] holds in zs-POSGs. We further proved that value functions—solutions of maximin (resp. minimax) equations—yield special structures. More specifically, the maximin value functions are convex whereas the minimax value functions are concave. We also showed how our results apply to more restrictive settings, essentially leading to more concise information. Together these findings allow us to introduce a key algorithm avoiding exhaustive enumeration of doubly exponentially many pure strategies, as suggested so far. We further illustrate the use of our algorithm through numerical examples.

7.5.3.3. Decentralized Markov decision processes in open systems: models and first algorithms

Participants: Jilles S. Dibangoye, Abdel-Illah Mouaddib [Univ. Caen Basse-Normandie], Jonathan Cohen [Univ. Caen Basse-Normandie].

Many real-world multiagent applications, e.g., rescue operations, require to dynamically assemble or disassemble teams needed to provide a service based on agents entering or quitting the system. While Decentralized Partially Observable Markov Decision Processes (Dec-POMDPs) formalize decision-making by multiple agents, they fail to exploit the team flexibility. Queueing models can formalize birth-death processes by which agents enter or exit a team, but they fail to capture multiagent planning under uncertainty. This work, in the context of the PhD work of J. Cohen, introduces a new model synthesized from Dec-POMDPs and birth-death processes, called open Dec-POMDPs. The primary result is the proof that the latter is NEXP-Complete. Exploiting the team flexibility, enables us to present a best-response dynamics' algorithm, which can dynamically adapt to agents entering or quitting a team and computes local optimum solutions.

7.5.3.4. Does randomization makes cooperative multi-agent planning easier?

Participant: Jilles S. Dibangoye.

These recent years have seen significant progress in multi-agent planning problems formulated as decentralized partially observable Markov decision processes (Dec-POMDPs). In state-of-the-art algorithms, agents use policies that do not employ random devices, i.e., deterministic policies, which are simple to handle and to implement, and yet are good candidates to be optimal. Integer linear programming (ILP) or constraint optimization programming (COP) can formalize the search for deterministic policies, unfortunately their worst case complexity (NP-Complete) suggest to be little hope for optimally solving real-world instances. In this paper, we show—for the first time—that the randomization allows us to use linear programming (LP) instead of ILP while preserving optimality, which drops the worst-case complexity from NP to P. Specifically, we introduce the first linear programs for incrementally approaching the optimal value function starting from upper- and lower-bound functions. We further extends state-of-the-art algorithm for Dec-POMDPs to use randomized policies. Finally, empirical results demonstrate significant improvements in time needed to find an ε-optimal solution on all tested benchmarks.

7.5.3.5. Reinforcement learning approach for active perception using multiple robots

Participants: Jilles S. Dibangoye, Jacques Saradaryan, Laëtitia Matignon, Trad Ahmed Yahia [Master Internship], Lorcan Charonnat [Internship INSA], Yuting Zhang [Internship INSA], Yifan Xiong [Internship INSA].

We consider cooperative, decentralized stochastic control problems represented as a decentralized partially observable Markov decision process. A critical issue that limits the applicability of that setting to realistic domains is how agents can learn to act optimally by interacting with the environment and with one another, given only an incomplete knowledge about the model. Reinforcement learning has previously been applied to decentralized decision making with a focus on distributed methods, which often results in suboptimal solutions. On the contrary, we build upon the idea that plans that are to be executed in a decentralized fashion can nonetheless be formulated in a centralized manner using a generative model of the environment. Following this line of thought, we propose the first (centralized) reinforcement learning algorithm for computing the optimal Q-value functions for cooperative, decentralized stochastic control problems. Experiments show our approach can learn to act optimally in many domains from the literature. We currently investigate robotic applications of this approach, including unknown scene reconstruction by a fleet of mobile robots.

8. Bilateral Contracts and Grants with Industry

8.1. Bilateral Contracts with Industry

8.1.1. Toyota Motors Europe

[2006 - 2017]

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

[2010 - 2017]

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) Nano-electronic 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).

8.2. Bilateral Grants with Industry

8.2.1. INSA-VOLVO Chair PhD grant

[Oct 2016 - Oct 2019]

This grant is linked to the PhD Thesis of Guillaume Bono, funded by the INSA-VOLVO Chair. The objective is to deal with Global-local Optimization Under Uncertainty for Goods Distribution Using a Fleet of Autonomous Vehicles.

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".

9.1.2. Projet AAP ARC6 (2016-19)

Participants: Gérard Bailly [CNRS, GIPSA Lab. Grenoble], Olivier Simonin, Anne Spalanzani.

Regional project (Rhône-Alpes) "TENSIVE Robots de TEléprésence : Navigation Sociale et Interaction VErbale immersives" ARC6, 2016-2019. Leader : G. Bailly.

This project funds the PhD thesis of Remi Cambuzat who started on october 2016, and co-advized by G. Bailly (Dir.), O. Simonin and A. Spalanzani.

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, [70]) 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 7.3.1 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 has started on february 2016 and is co-supervized 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 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).
- University of Babes-Bolyai, Cluj-Napoca, Romania.

  Subject: Multi-robot patrolling and Machine Learning (Visit and PHC "DRONEM" 2017-18 obtained in December 2016).
- 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 [41] 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.

9.4.2. Inria Associate Teams Not Involved in an Inria International Labs

9.4.2.1. SAMPEN

Title: self adaptive mobile perception and navigation

International Partner (Institution - Laboratory - Researcher):

Start year: 2014

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.

9.4.3. Inria International Partners

9.4.3.1. Informal International Partners

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

- 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.

9.4.4. 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.

10. Dissemination

10.1. Promoting Scientific Activities

10.1.1. Scientific Events Organisation

10.1.1.1. General Chair, Scientific Chair

- O. Simonin was co-chair of the Workshop DEMUR "On-line decision-making in multi-robot coordination” at International Conf. RSS, Ann Arbor, University of Michigan, June 2016.
- O. Simonin was General chair of the 2eme Journée nationale Robotique & IA., Clermont-Ferrand, RFIA 2016, 27 juin 2016.
- C. Laugier, Ph. Martinet, C. Stiller and U. Nunes, organized a workshop entitled "8th Workshop on Planning, Perception and Navigation for Intelligent Vehicles - A bridge between Robotics and ITS technologies" at IEEE ITSC 2016, Rio de Janeiro, November 1st 2016 (about 90 attendees).
- C. Laugier has been appointed as Program co-chair for IEEE/RSJ IROS 2018 (Madrid) and General co-Chair of IEEE/RSJ IROS 2019 (Hong Kong).

10.1.1.2. Member of the Organizing Committees

- C. Laugier was Associate Editor for IEEE/RSJ IROS 2016, for IEEE ICRA 2016, and for IEEE ITSC 2016.

10.1.2. Scientific Events Selection

10.1.2.1. Member of the Conference Program Committees

- Jilles S. Dibangoye was Program Committee member of the following conferences:
  - International Joint Conference on Artificial Intelligence (IJCAI)
  - Autonomous Agent and Multi-agent Systems International Conference (AAMAS)
- O. Simonin is Program Committee member for Autonomous Agent and Multi-agent Systems International Conference (AAMAS) Special Track 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 2016, IROS 2016, ACC 2016.
- O. Simonin served, in quality of reviewer, at the following international conferences : IROS 2016, ICRA 2016.

10.1.3. Journal

10.1.3.1. Member of the Editorial Boards

- C. Laugier is Member of the Steering Committee of the journal IEEE Transaction on Intelligent Vehicles.
- C. Laugier Senior Editor of the journal IEEE Transaction on Intelligent Vehicles.
- C. Laugier is member of the Editorial Board of the journal IEEE ROBOMECH
- O. Simonin is a member of the editorial board of RIA Revue d'Intelligence Artificielle.

10.1.3.2. Reviewer - Reviewing Activities

- A. Martinelli served, in quality of reviewer, for the following journals: Transaction on Automation Science and Engineering, IEEE Robotics and Automation Letters.
- 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 Autonomous Robots Journal (AURO) and the Revue d'Intelligence Artificielle (RIA).

10.1.4. Invited Talks

Anne Spalanzani was invited to give a talk at

- Xerox (Meylan), september 2016.
- the conference RFIA (Clermont Ferrand), June 2016.
- the journées scientifique d'Inria (Rennes), June 2016.

Agostino Martinelli was invited to give a talk at

- Centro Piaggio, University of Pisa, June 2016, “Nonlinear Unknown Input Observability: the General Analytic Solution”.
- Automation Lab, University of Tor Vergata, Rome, December 2016, “Nonlinear Unknown Input Observability: the General Analytic Solution”.
- Vision and Perception lab., University of Zurich, December 2016, “Visual-Inertial Sensor Fusion”.

Christian Laugier was invited to give a talk at

- IEEE ICIT 2016, Session on Cognitive Systems and Automation for Service Robotics and Intelligent Mobility, Taipei, March 2016, "Bayesian Perception & Decision for Autonomous Vehicles and Mobile Robots”.
- Mediatek International Company, Hsinchu, Taiwan, March 15th 2016, “Bayesian Perception Technologies and Industrial Applications”.
- City-U Seminar, Hong Kong, April 22nd 2016, “Bayesian Perception & Decision for Autonomous vehicles and Mobile Robots”.
- Robotics Symposium, CUHK, T-Stone Robotics Institute, Hong Kong, April 21-22 2016, “Embedded Bayesian Perception & Decision-making for Autonomous Mobility in Dynamic Human Environments”.
- IEEE ARSO 2016, Plenary talk, Shanghai, July 2016, “Towards Fully Autonomous Driving ? The Perception & Decision-Making Bottleneck”.

Olivier Simonin was invited to give a talk at

- Université de Babes-Bolyai, Cluj-Napoca, Romania, July 2016.
- Workshop SAMPEN, Lyon, Januray 27, 2016.
- Robotics Times Connect, Lyon, December 7, 2016.

10.1.5. Leadership within the Scientific Community

- C. Laugier is co-chair with Philippe Martinet and Christoph Stiller, of the IEEE RAS Technical Committee on "Autonomous Ground Vehicles and Intelligent Transportation Systems (AGVITS)".
- C. Laugier is member of the Committee "safety of autonomous vehicles" (committee leaded by ARDI in the scope of the Innovation Regional Strategy).

10.1.6. Scientific Expertise

- C. Laugier has been invited as a panel member of the evaluation committee of "Beijing Institute of Technology (BIT)". A three days evaluation seminar has been held in Beijing on November 9-11, 2016.
- C. Laugier is Scientific Consultant for the Probayes company.
- O. Simonin is member of the 2017 ANR scientific committee.

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

INSA Lyon 5th year : O. Simonin, resp. of the Robotics option : AI for Robotics, Software and Hardware for robotics, Robotics projects, 50h, M2, Dept. Telecom 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

INSA Lyon 5th year : A. Spalanzani, Navigation en environnement humain, 2h, M2, INSA de Lyon, France.

E-learning

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, 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.

PhD in progress: Pavan Vasishta, behavioral modeling in urban environments. A. Spalanzani and D. Vaudreydaz (Pervasive Interaction), started in Feb. 2016.

PhD in progress: Mihai Popescu, Robot fleet mobility under communication constraints, 2015, O. Simonin, A. Spalanzani, F. Valois (Agora), Regional funding.

Starting PhD: Guillaume Bono, Global-local Optimization Under Uncertainty for Goods Distribution Using a Fleet of Autonomous Vehicles, O. Simonin, J. Dibangoye, L. Matignon, INSA-Volvo Chair funding.

Starting PhD: Remi Cambuzat, Robots de TEléprésence : Navigation Sociale et Interaction VErbale immersives, G. Bailly (CNRS GIPSA lab), A. Spalanzani, O. Simonin, Regional funding.

10.2.3. Juries

- O. Simonin was a member (president) of the defense committee of the PhD thesis of Emmanuel Hermellin, Univ. de Montpellier, LIRMM, November 18, 2016.
- O. Simonin was a member of the defense committee of the PhD thesis of Arnaud Paris, Université d'Orléan, Labo PRISME, Bourges, October 17, 2016.
- O. Simonin was a member of the defense committee of the PhD thesis of Patrick Bechon, Université de Toulouse, ISAE Supaero, May 26, 2016.
- O. Simonin was a member (president) of the defense committee of the PhD thesis of Osamah Saif, Université de Technologie de Compiègne UTC, March 23, 2016.
- O. Simonin was a member (president) of the defense committee of the PhD thesis of Zhicheng Hou, Université de Technologie de Compiègne UTC, February 10, 2016.
- A. Spalanzani was a reviewer and a member of the defense committee of the PhD thesis of Omar Adair Islas Ramìrez, Université Pierre et Marie Curie, November 28th, 2016.
- A. Spalanzani was a member of the defense committee of the PhD thesis of Suman Raj Bista, Université de Rennes 1, December 20th, 2016.
- C. Laugier was reviewer and member of the defense committee of the PhD thesis of Alexandre Armand (ENSTA ParisTech, May 31 2016).

11. Bibliography

Major publications by the team in recent years

[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] 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

[3] J. S. DIBANGOYE, O. BUFFET, O. SIMONIN. *Structural Results for Cooperative Decentralized Control Models*, in "24th International Joint Conference on Artificial Intelligence (IJCAI)", 2015, pp. 46–52

[4] J. KAISER, A. MARTINELLI, F. FONTANA, D. SCARAMUZZA. *Simultaneous State Initialization and Gyroscope Bias Calibration in Visual Inertial aided Navigation*, in "IEEE Robotics and Automation Letters", January 2016, https://hal.archives-ouvertes.fr/hal-01423550

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

[6] P. PAPADAKIS, A. SPALANZANI, C. LAUGIER. *Social Mapping of Human-Populated Environments by Implicit Function Learning*, in "IEEE International Conference on Intelligent Robots and Systems", Tokyo, Japan, 2013, https://hal.inria.fr/hal-00860618

[7] M.-I. POPESCU, H. RIVANO, O. SIMONIN. *Multi-robot Patrolling in Wireless Sensor Networks using Bounded Cycle Coverage*, in "ICTAI 2016 28th International Conference on Tools with Artificial Intelligence", San Jose, United States, IEEE, November 2016, https://hal.archives-ouvertes.fr/hal-01357866

[8] T. RAKOTOVAO, J. MOTTIN, D. PUSCHINI, C. LAUGIER. *Multi-sensor fusion of occupancy grids based on integer arithmetic*, in "In 2016 IEEE International Conference on Robotics and Automation (ICRA)", 2016

[9] 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

[10] 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

Publications of the year

Articles in International Peer-Reviewed Journals

[11] J. S. DIBANGOYE, C. AMATO, O. BUFFET, F. CHARPILLET. *Optimally Solving Dec-POMDPs as Continuous-State MDPs*, in "Journal of Artificial Intelligence Research", February 2016, vol. 55, pp. 443-497 [*DOI :* 10.1613/JAIR.4623], https://hal.inria.fr/hal-01279444

[12] J. KAISER, A. MARTINELLI, F. FONTANA, D. SCARAMUZZA. *Simultaneous State Initialization and Gyroscope Bias Calibration in Visual Inertial aided Navigation*, in "IEEE Robotics and Automation Letters", January 2016, https://hal.archives-ouvertes.fr/hal-01423550

Articles in National Peer-Reviewed Journals

[13] M. TLIG, O. BUFFET, O. SIMONIN. *Intersections intelligentes pour le contrôle de véhicules sans pilote : coordination locale et optimisation globale*, in "Revue des Sciences et Technologies de l'Information - Série RIA : Revue d'Intelligence Artificielle", 2016, https://hal.inria.fr/hal-01330354

Invited Conferences

[14] C. LAUGIER. *Bayesian Perception & Decision for Autonomous Vehicles and Mobile Robots (Invited Talk)*, in "IEEE ICIT 2016", Taipei, Taiwan, Prof Ren Luo, March 2016, https://hal.inria.fr/hal-01435868

[15] C. LAUGIER. *Embedded Bayesian Perception & Decision-making for Autonomous Mobility in Dynamic Human Environments (Invited Talk)*, in "Robotics Symposium, CUHK Robotics Institute", Hong Kong, Hong Kong SAR China, April 2016, https://hal.inria.fr/hal-01428627

[16] C. LAUGIER. *Embedded Perception & Risk Assessment for next Cars Generation (Invited Talk)*, in "Asprom-Cap'Tronic-UIMM seminar: "De la voiture connectée à la voiture Autonome : Technologies, Enjeux et Applications »", Paris, France, Asprom-Cap'Tronic-UIMM, February 2016, https://hal.inria.fr/hal-01428211

[17] C. LAUGIER. *Towards Fully Autonomous Driving ? The Perception & Decision-making bottleneck (Plenary Talk)*, in "IEEE ARSO 2016", Shanghai, China, Proceedings of IEEE ARSO 2016, July 2016, vol. 2016, https://hal.inria.fr/hal-01435861

International Conferences with Proceedings

[18] M. BARBIER, C. LAUGIER, O. SIMONIN, J. IBANEZ-GUZMAN. *Functional Discretization of Space Using Gaussian Processes for Road Intersection*, in "2016 IEEE 19th International Conference on Intelligent Transportation Systems (ITSC 2016)", Rio de Janeiro, Brazil, proceedings of the 2016 IEEE 19th International Conference on Intelligent Transportation Systems (ITSC 2016, IEEE Intelligent Transportation Systems Society, November 2016, 7 p. , https://hal.inria.fr/hal-01362223

[19] S.-G. CHITIC, J. PONGE, O. SIMONIN. *SDfR -Service discovery for multi-robot systems*, in "ICAART 2016 The 8th International Conference on Agents and Artificial Intelligence", Rome, Italy, February 2016, https://hal.archives-ouvertes.fr/hal-01286895

[20] J. COHEN, L. MATIGNON, O. SIMONIN. *Incremental and adaptive multi-robot mapping for human scene observation*, in "ICTAI 2016 28th International Conference on Tools with Artificial Intelligence", San Jose, United States, IEEE, November 2016, https://hal.archives-ouvertes.fr/hal-01357857

[21] J. KAISER, A. MARTINELLI, F. FONTANA, D. SCARAMUZZA. *Simultaneous State Initialization and Gyroscope Bias Calibration in Visual Inertial aided Navigation*, in "ICRA 2016", stockholm, Sweden, May 2016, https://hal.archives-ouvertes.fr/hal-01423557

[22] V. KARAKKAT NARAYANAN, A. SPALANZANI, M. BABEL. *A semi-autonomous framework for human-aware and user intention driven wheelchair mobility assistance*, in "IEEE/RSJ Int. Conf. on Intelligent Robots and Systems, IROS'16", Daejeon, South Korea, October 2016, pp. 4700-4707, https://hal.inria.fr/hal-01355481

[23] V. KARAKKAT NARAYANAN, A. SPALANZANI, R. C. LUO, M. BABEL. *Analysis of an adaptive strategy for equitably approaching and joining human interactions*, in "IEEE Int. Symp. on Robot and Human Interactive Communication, RO-MAN", New-York, United States, IEEE Int. Symp. on Robot and Human Interactive Communication, RO-MAN, August 2016, https://hal.inria.fr/hal-01330889

[24] C. LAUGIER, J. CHARTRE. *Intelligent Perception and Situation Awareness for Automated vehicles*, in "Conference GTC Europe 2016", Amsterdam, Netherlands, September 2016, https://hal.inria.fr/hal-01428547

[25] M.-I. POPESCU, H. RIVANO, O. SIMONIN. *Multi-robot Patrolling in Wireless Sensor Networks using Bounded Cycle Coverage*, in "ICTAI 2016 28th International Conference on Tools with Artificial Intelligence", San Jose, United States, IEEE, November 2016, https://hal.archives-ouvertes.fr/hal-01357866

[26] D. SIERRA GONZÁLEZ, J. S. DIBANGOYE, C. LAUGIER. *High-Speed Highway Scene Prediction Based on Driver Models Learned From Demonstrations*, in "Proceedings of the 2016 IEEE 19th International Conference on Intelligent Transportation Systems (ITSC 2016)", Rio de Janeiro, Brazil, November 2016, https://hal.inria.fr/hal-01396047

[27] 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

National Conferences with Proceedings

[28] J. SARAYDARYAN, F. JUMEL, O. SIMONIN. *Patrouille Multi-Agent Dynamique, application en Robotique au Service de Personnes Mobiles*, in "Journées Francophones sur les Systèmes Multi-Agents (JFSMA) 2016", Rouen, France, October 2016, https://hal.archives-ouvertes.fr/hal-01357609

Conferences without Proceedings

[29] J. CHARTRE, L. RUMMELHARD, A. NÈGRE, J.-A. DAVID, J. LUSSEREAU, C. LAUGIER. *Situation Awareness for Intelligent Mobility in Dynamic Environments IRT Nanoelec Perfect Platform*, in "5th International conference on Machine Control & Guidance", Vichy, France, October 2016, https://hal.inria.fr/hal-01393287

[30] J. SARAYDARYAN, F. JUMEL, O. SIMONIN. *Modeling human flows from robots perception : application to navigation in dynamic environment*, in "RSS Workshop On-line decision-making in multi-robot coordination", Ann Arbor, United States, June 2016, https://hal.archives-ouvertes.fr/hal-01357791

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[31] A. BROGGI, A. ZELINSKY, U. OZGUNER, C. LAUGIER. *Handbook of Robotics 2nd edition, Chapter 62 on "Intelligent Vehicles"*, in "Handbook of Robotics 2nd Edition", B. SICILIANO, O. KHATIB (editors), July 2016, https://hal.inria.fr/hal-01260280

Other Publications

[32] C. LAUGIER. *Autnonomous Vehicles: Societal and Technological Evolution (Invited Contribution)*, December 2016, Table ronde "Vehicule Autonome et Ville de Demain - Technologie, Business et Société: Quels enjeux ?" Issy-les-Moulineaux, https://hal.inria.fr/hal-01437003

[33] C. LAUGIER. *Bayesian Perception & Decision for Autonomous Vehicles and Mobile Robots: From Research to Industrial Applications*, March 2016, Invited talk at MediaTek, Taipei, https://hal.inria.fr/hal-01436967

[34] C. LAUGIER. *Bayesian Perception & Decision-making for Robot Navigation in Dynamic Environments (Invited Talk)*, April 2016, Invited talk at CityU Hong Kong, https://hal.inria.fr/hal-01436976

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[40] B. BELO. *3 Known Landmarks are Enough for Solving Planar Bearing SLAM and Fully Reconstruct Unknown Inputs*, in "Intelligent Robots and Systems (IROS)", IEEE, 2010

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[44] G. FERRER, A. SANFELIU. *Bayesian Human Motion Intentionality Prediction in urban environments*, in "Pattern Recognition Letters", 2014, vol. 44, n^o 0, pp. 134 - 140, Pattern Recognition and Crowd Analysis [*DOI :* 10.1016/J.PATREC.2013.08.013], http://www.sciencedirect.com/science/article/pii/S0167865513003176

[45] C. FORSTER, L. CARLONE, F. DELLAERT, D. SCARAMUZZA. *IMU Preintegration on Manifold for Efficient Visual-Inertial Maximum-a-Posteriori Estimation*, in "RSS", 2015

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