Activity Report 2013

Project-Team E-MOTION

Geometry and Probability for Motion and Action

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<div align="center">**Project-Team E-MOTION**</div>

Keywords: Robotics, Risk Analysis, Human Assistance, Perception, Robot Motion

Creation of the Project-Team: 2004 February 01.

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2. Overall Objectives

2.1. Introduction

Main challenge: The overall objective of the Project team *e-Motion* is to address some fundamental and open issues located at the heart of the emerging research field called "Human Centered Robotics". More precisely, our goal is to develop *Perception, Decision, and Control* algorithmic models whose characteristics fit well with the constraints of human environments; then, these models have to be embedded into *"artificial systems"* having the capability to evolve safely in human environments while having various types of interactions with human beings. Such systems have to exhibit sufficiently efficient and robust behaviors for being able to operate in *open and dynamic environments*, i.e., in partially known environments, where time, dynamics and interactions play a major role. Recent technological progress on embedded computational power, on sensor technologies, and on miniaturized mechatronic systems, make the required technological breakthroughs potentially possible (including from the scalability point of view).

Approach and research themes: Our approach for addressing the previous challenge is to combine the respective advantages of *Computational Geometry* and of *Theory of Probabilities*, while working in cooperation with neurophysiologists for the purpose of taking into account Human perception and navigation models. Two main research themes are addressed under both the algorithmic and human point of views; these research themes are respectively related to the problems of *understanding dynamic scenes in human environments* and of *navigating interactively and safely in such environments*.

- *Perception & Situation awareness in Human environments*. The main problem is to understand complex dynamic scenes involving human beings, by exploiting prior knowledge and a flow of perceptive data coming from various sensors. Our approach for solving this problem is to develop three complementary paradigms:
    - *Bayesian Perception*: How to take into account prior knowledge and uncertain sensory data in a dynamic context?
    - *Risk Assessment*: How to evaluate this collision risk (i.e., potential future collisions) from an estimate of the current state of the dynamic scene, and from the prediction of the future behaviors of the scene participants?
    - *Behavior modeling & Learning*: How to model and to learn behaviors from observations?

- *Navigation, Control, and Interaction in Human environments*. The main problem is to take safe and socially acceptable goal-oriented navigation and control decisions, by using prior knowledge about the dynamic scenario and the related social rules, and by fusing noisy sensory data in order to estimate the state parameters. Our approach for addressing this problem is to develop two complementary concepts:
    - *Human-Aware Navigation*: How to navigate safely towards a given goal in a dynamic environment populated by human beings, while taking into account human-robot interactions and while respecting social rules and human comfort ?
    - *State Estimation & Control*: How to estimate the state parameters from noisy and sometime missing sensory data ? How to control a robot or a fleet of robots for executing a task in a near optimal way ?

2.2. Highlights of the Year

Awards :

- C . Laugier, Ph. Martinet and C. Stiller have received the "Most Active IEEE RAS Technical Committee Award of the year 2013" for the Technical Committee they are co-chairing on "Autonomous Ground Vehicles and Intelligent Transportation Systems". This prize has been announced during the award ceremony of the annual IEEE ICRA conference in Karlsruhe.

- C. Laugier has been invited by the French Ministry of Foreign Affairs and by the Taiwan Office in Paris to participate has a French Robotics Expert, to the high level French delegation conducted by Mme Edith Cresson (former prime minister), October 2013.

- C. Laugier was a member of the Best paper Award Committee of the IEEE ICRA 2013 conference, Karlsruhe, May 2013.

- C. Laugier was chair of the Best paper Award Committee of the 5th PPNIV Workshop organized in the scope of the IEEE/RSJ IROS 2013 conference. The prize was given by the IEEE RAS Technical Committee on "Autonomous Ground Vehicles and Intelligent Transportation Systems".

Patents:

- S. Lefevre, C. Laugier, and J. Ibanez-Guzman have submitted a patent (Inria and Renault) on "Method and process for the evaluation of the risk of collision at intersections". The patent has initially been submitted in 2012 and finalized in 2013.

- I. Paromtchik and C. Laugier have submitted in 2013 a patent on "Method and apparatus for improving driving safety of a vehicle travelling on a road". Patent no. 13305275.3-1803.

- S. Lefevre, C. laugier and R. Bajcsy have submitted in 2013 a patent (Inria and UC Berkeley) on "Decision Making for Collision Avoidance Systems". Patent no. 13306495.6-1810.

Invited talks:

- C. Laugier has given an invited talk entitled "Road Scene Understanding using Bayesian Perception & Risk Assessment" at the Colloquium on Intelligent Robots and Systems, Osaka, June 14th 2013.

- C. Laugier has given an invited talk entitled "Embedded Bayesian Perception and Situation Awareness for Mobile Robots" at a NTU-iCeiRA Seminar on Intelligent Robotics, Taipei, May 2013.

- C. Laugier has given an invited lecture entitled "Embedded Bayesian Perception and Situation Awareness Robots & Intelligent Vehicles" at Toyota Technological Institute, Nagoya, June 2013.

- C. Laugier has given an invited talk entitled "Embedded Perception & Risk Assessment for Intelligent Vehicles" at the Workshop "Vehicle Autonomy in Urban Transportation Systems" IEEE ICRA 2013, Karlsruhe, May 10th 2013.

- C. Laugier has given a keynote talk entitled "Road Scenes Understanding & Risk Assessment using Embedded Bayesian Perception" at the 5th PPNIV Workshop, IEEE IROS 2013, Tokyo, November 2013.

- C. Laugier has given an introductory talk entitled "Embedded Perception for Future Cars" at the Seminar In'Tech "Perception embarquée pour les véhicules de demain", Inria Grenoble Rhône-Alpes, Grenoble, October 24th 2013.

- C. Laugier and A. Spalanzani have given a tutorial on "Autonomous Robotics" at the ISIE 2013 Conference, Taipei, May 2013.

3. Application Domains

3.1. Introduction

The main applications of our research are those aiming at introducing advanced and secured robotized systems into human environments. In this context, we are focusing onto the following application domains: Future cars and transportation systems, Service and Human assistance robotics, and Potential spin-offs in some other application domains.

3.2. 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 laboratories. These technologies are progressively arriving at maturity, as it is witnessed by the results of large scale experiments and challenges (e.g., Darpa Urban Challenge 2007) and by the fast development of ambitious projects such as the Google's car project. Moreover, the legal issue starts to be addressed (see for instance the recent laws in Nevada and in California authorizing autonomous vehicles on roads).

In this context, we are interested in the development of *ADAS* [1] 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).

3.3. Service, intervention, and human assistance robotics

This application domain is currently quickly emerging, and more and more industrials 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. A more recent challenge for the coming decade is to develop robotized systems for assisting elderly and/or disabled people. We are strongly involved in the development of such technologies, which are clearly tightly connected to our research work on robots in human environments.

3.4. Potential spin-offs in some other application domains

Our *Bayesian Programming* tools (including the functions for decision making under uncertainty) are also impacting a large spectrum of application domains such as autonomous systems, surveillance systems, preventive maintenance for large industrial plants, fraud detection, video games, etc. These application domains are covered by our start-up *Probayes*.

4. Software and Platforms

4.1. PROTEUS Software

Participants: Amaury Nègre, Juan Lahera-Perez.

This toolkit offers a automatic mobile robot driver, some sensors drivers sensors as Sick laser, GPS, motion tracker, mono or stereo camera), and a 3D Simulator.

The latest developments have been focuses on the robotics simulator. This simulator is based on the simulation and 3D rendering engine "mgEngine" (http://mgengine.sourceforge.net/) embedded with the physics engine "bullets physics" (http://bulletphysics.org) for realistic robot dynamic simulation.

We also worked on the interface with the robotics middleware "ROS" (http://www.ros.org) in order to offer interoperability with many robotics applications.

The simulator is now fully integrated with the robotics middleware "ROS" (http://www.ros.org) which allow interoperability with a large set of robotics applications and visualization tools. This software is developed in C++ and the simulator operates with the Lua scripting language. The simulation software is used in the ANR Proteus (http://www.anr-proteus.fr), as a simulation engine for the PROTEUS Toolkit.

- Version: 2.0
- APP:IDDN.FR.001.510040.000.S.P.2005.000.10000
- Programming language: C/C++, Lua

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[1] Advanced Driver Assistance Systems

4.2. AROSDYN

Participants: Igor Paromtchik, Mathias Perrollaz, Alexandros Makris, Amaury Nègre, Christian Laugier.

ArosDyn (http://arosdyn.gforge.inria.fr/) is a system which integrates our recently developed techniques to provide a real-time collision risk estimation in a dynamic environment. The main features of this software are:

1. The design provides high maintainability, scalability and reuseness of the models and algorithms.
2. The software has a user interface (UI) which is user-friendly.
3. The software facilitates the parameter tuning of the models.
4. It uses the GPU to accelerate the computation.
5. Working together with the Hugr middleware (http://gforge.inria.fr/projects/cycabtk), it can run on our experimental vehicle in real-time.

Another important property of this software is a large part of the computation task executed on GPU. As the processing of stereo image and the computaion in the BOF can be highly parallelized, we run these tasks on the GPU to improve the time performance. The GPU calculation is based on CUDA library and is carried out in an independent thread.

Furthermore, thanks to the design of the software, we can easily add new models to it and let them work together. The fast detection and tracking algorithm (FCTA) and the Gaussian process based collision assessment algorithm are added into this framework. The sofware is implemented on the Lexus car. In 2012, a demand for deposing the GPU BOF software to the APP is in progress.

4.3. Embedded Perception

Participants: Mathias Perrollaz, Amaury Nègre, Christian Laugier.

The method for computing occupancy grids from a stereoscopic sensor, developed 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.

The program has been deposed to the APP in 2012, under the reference: IDDN.FR.001.270004.000.S.P.2012.000.10800

4.4. Bayesian Occupancy Filter

People involved: Kamel Mekhnacha, Tay Meng Keat Christopher, C. Laugier, M. Yguel, Pierre Bessière.
The BOF toolbox is a C++ library that implements the Bayesian Occupancy Filter. It is often used for modelling dynamic environments. It contains the relevant functions for performing bayesian filtering in grid spaces. The output from the BOF toolbox are the estimated probability distributions of each cell's occupancy and velocity. Some basic sensor models such as the laser scanner sensor model or Gaussian sensor model for gridded spaces are also included in the BOF toolbox. The sensor models and BOF mechanism in the BOF toolbox provides the necessary tools for modelling dynamic environments in most robotic applications. This toolbox is patented under two patents : "Procédé d'assistance à la conduite d'un véhicule et dispositif associé" n. 0552735 (9 september 2005) and "Procédé d'assistance à la conduite d'un véhicule et dispositif associé amélioré" n. 0552736 (9 september 2005) and commercialized by ProBayes.

- Version: 1
- Patent: 0552736 (2005), 0552735 (2005)
- Programming language: C/C++

4.5. PROBT

People involved: Juan-Manuel Ahuactzin, Kamel Mekhnacha, Pierre Bessière, Emmanuel Mazer, Manuel Yguel, Christian Laugier.

ProBT is both available as a commercial product (ProBAYES.com) and as a free library for public research and academic purposes (http://emotion.inrialpes.fr/BP/spip.php?rubrique6). Formerly known as *OPL*, *ProBT* is a C++ library for developing efficient Bayesian software. It is available for Linux, Unix, PC Windows (Visual C++), MacOS9, MacOSX and Irix systems. The ProBT library (http://www.probayes.com/) has two main components: (i) a friendly Application Program Interface (API) for building Bayesian models, and (ii) a high-performance Bayesian Inference Engine (BIE) allowing to execute all the probability calculus in exact or approximate way. *ProBT* is now commercialized by our start-up *Probayes*; it represents the main Bayesian programming tool of the *e-Motion* project-team, and it is currently used in a variety of external projects both in the academic and industrial field (e.g., for the European project BACS and for some industrial applications such as Toyota or Denso future driving assistance systems).

5. New Results

5.1. Perception and Situation Awareness in Dynamic Environments

5.1.1. *Sensor Fusion for state parameters identification*
Participants: Agostino Martinelli, Chiara Troiani.

5.1.1.1. *General theoretical results*

We continued to investigate the visual-inertial structure from motion problem by further addressing the two important issues of observability and resolvability in closed form. Regarding the first issue, we extended our previous results published last year on the journal of Transaction on Robotics [44] by investigating the case when the visual sensor is not extrinsically calibrated. In order to deal with this case, we must augment the state to be estimated by including all the parameters that characterize the extrinsic camera calibration, i.e., the six parameters that describe the relative transformation between the frame attached to the camera and the frame attached to the Inertial Measurement Unit (IMU). On the other hand, because of the larger size of the resulting state, it became prohibitive a direct application of the method that we introduced two years ago (see [43]) in order to discover the observability properties for this new state. For this reason, our first novel contribution during this year was the introduction of new methodologies able to significantly reduce the computational burden demanded by the implementation of the method in [43]. These methodologies have been published in [22] and a deeper description of their use is currently under revision on the journal Foundations and Trends in Robotics. The new results obtained by using these methodologies basically state that also the new six parameters that describe the camera extrinsic calibration are observable. Finally, we started a new research that in the literature is known as the Unknown Input Observability (UIO) and it is investigated by the automatic control community. We started this new research since we investigated the observability properties of the visual inertial structure from motion as the number of inertial sensors is reduced. Specifically, instead of considering the standard formulation, which assumes a monocular camera, three orthogonal accelerometers and three orthogonal gyroscopes, the considered sensor suit only consists of a monocular camera and one or two accelerometers. This analysis has never been provided before. A preliminary investigation seems to prove that the observability properties of visual inertial structure from motion do not change by removing all the three gyroscopes and one accelerometer. By removing a further accelerometer, if the camera is not extrinsically calibrated, the system loses part of its observability properties. On the other hand, as the camera is extrinsically calibrated, the system maintains the same observability properties as in the standard case. This contribution clearly shows that the information provided by a monocular camera, three accelerometers and three gyroscopes is redundant. Additionally, it provides a new perspective in the framework of neuroscience to the process of vestibular and visual integration for depth perception and self motion perception. Indeed, the vestibular system, which provides balance in most mammals, consists of two organs (the *utricle* and the *saccule*) able to sense the acceleration only along two independent axes (and not three). In order to analyze these systems with a reduced number of inertial sensors, we had to consider control systems where some of the inputs are unknown. Indeed, the visual-inertial structure from motion problem can be characterized by a control system where the inputs are known thanks to the inertial sensors. Hence, to deal with the visual-inertial

structure from motion as the number of inertial sensors is reduced, we had to introduce a new method able to address the more general UIO problem. We believe that our solution to the UIO is general and this is the reason because we started this new research domain in control theory. Preliminary results are currently under revision on the journal Foundations and Trends in Robotics and we also plan to present them at the next ICRA conference. Regarding the second issue, i.e., the problem resolvability in closed form, a new simple closed form solution to visual-inertial structure from motion has been derived. This solution expresses the structure of the scene and the motion only in terms of the visual and inertial measurements collected during a short time interval. This allowed us to introduce deterministic algorithms able to simultaneously determine the structure of the scene together with the motion without the need for any initialization or prior knowledge. Additionally, the closed-form solution allowed us to identify the conditions under which the visual-inertial structure from motion has a finite number of solutions. Specifically, it is shown that the problem can have a unique solution, two distinct solutions or infinite solutions depending on the trajectory, on the number of point-features and on their arrangement in the 3D space and on the number of camera images. All the results have been published on the international journal of Computer Vision [15].

5.1.1.2. Applications with a Micro Aerial Vehicle

We introduced a new method to localize a micro aerial vehicle (MAV) in GPS denied environments and without the usage of any known pattern [26]. The method exploits the planar ground assumption and only uses the data provided by a monocular camera and an inertial measurement unit. It is based on a closed solution which provides the vehicle pose from a single camera image, once the roll and the pitch angles are obtained by the inertial measurements. Specifically, the vehicle position and attitude can uniquely be determined by having two point features. However, the precision is significantly improved by using three point features. The closed form solution makes the method very simple in terms of computational cost and therefore very suitable for real time implementation. Additionally, because of this closed solution, the method does not need any initialization. Results of experimentation show the effectiveness of the proposed approach.

We proposed a novel method to estimate the relative motion between two consecutive camera views, which only requires the observation of a single feature in the scene and the knowledge of the angular rates from an inertial measurement unit, under the assumption that the local camera motion lies in a plane perpendicular to the gravity vector [27]. Using this 1-point motion parametrization, we provide two very efficient algorithms to remove the outliers of the feature-matching process. Thanks to their inherent efficiency, the proposed algorithms are very suitable for computationally-limited robots. We test the proposed approaches on both synthetic and real data, using video footage from a small flying quadrotor. We show that our methods outperform standard RANSAC-based implementations by up to two orders of magnitude in speed, while being able to identify the majority of the inliers.

5.1.2. A new formulation of the Bayesian Occupancy Filter : an hybrid sampling based framework

Participants: Lukas Rummelhard, Amaury Nègre.

The Bayesian Occupancy Filter (BOF) is a discretized grid structure based bayesian algorithm, in which the environment is subdivised in cells to which random variables are linked. These random variables represent the state of occupancy and the motion field of the scene, without any notion of object detection and tracking, making the updating part of the filter an evaluation of the distribution of these variables, according to the new data acquisition. In the classic representation of the BOF, the motion field of each cell is represented as a neighborhood grid, the probability of the cell moving from the current one to another of the neighborhood being stocked in an histogram. If this representation is convenient for the update, since the potential antecedents of any cell is exactly determined by the structure, and so the propagation model is easily parallelizable, it also raises determinant issues :

- the structure requires the process rate to be constant, and a priori known.
- in the case of a moving grid, such as an application of car perception, many aliasing problems can appear, not only in the occupation grid, but in the motion fields of cells. A linear interpolation in 4-dimension field to fill each value of the histograms can quickly become unreasonable.

- to be able to match the slowest moves in the scene and the tiniest objects, the resolution of the grid and the motion histogram must be the high. On the other hand, since the system must be able to evaluate the speed of highly dynamic objects (typically, a moving car), the maximum encoded speed is to be high as well. This results in a necessary huge resolution grid, which prevent the system from being used with satisfying results on an embedded device. This huge grid is also mostly empty (most of the motion field histogram for a occupied cell will be empty). On top of that, the perception system being used to represent the direct environment of a moving car, the encoded velocity is a relative velocity, which implies, if we consider the maximal speed of a car to be V_max, to maintain a motion field able to represent speeds from $-2 * V_{max}$ to $2 * V_{max}$. The necessity of such a sized structure is a huge limitation of practical use of the method.

Considering those limitations, a new way to represent the motion field has been developped. To do so, a new formulation of the BOF has been elaborated. This new version allow to introduce in the filter itself a distinction between static and dynamic parts, and so adapt the computation power. The main idea of this new representation is to mix two forms of sampling : a uniform one, represented as a grid, for the static objects and the empty areas, and a non uniform one, based on particles drawn from dynamic regions. The motion field in a cell will be represented as a set of samples from the distribution for values which are not null, and a weight given to the static hypothesis. The use of a set of samples to represent the motion field leads to a important decrease of the needed memory space, as well as the classification between dynamic objects and static objects or free areas. In the updating process, the antecedent of a cell can be either from the static configuration or from the dynamic configuration, which are both way easier to project in the new reference frame of the moving grid. The first results are stimulating, in term of occupancy evaluation and mostly in term of velocity prediction, being way more accurate and responsive than the older version. Those improvements will soon be presented in detail in upcoming papers, one being currently in the process of redaction.

5.1.3. DATMO

Participants: Dung Vu, Mathias Perrollaz, Amaury Nègre.

In the current work, we have been developing a general framework for tracking multiple targets from lidar data.

In the past decades, multiple target tracking has been an active research topic. When object observations are known, object tracking becomes a data association (DA) problem. Among popular DA methods, multiple hypothesis tracking (MHT) is widely used. MHT is a multi-frame tracking method that is capable of handling ambiguities in data association by propagating hypotheses until they can be solved when enough observations are collected. The main disadvantage of MHT is its computational complexity since the number of hypotheses grows exponentially over time. The joint probabilistic data association (JPDA) filter is more efficient but prone to make erroneous decision since only single frame is considered and the association made in the past is not reversible. Other sequential approaches using particle filters share the same weakness that they cannot reverse time back when ambiguities exist. All DA approaches mentioned above requires a strong assumption of one-to-one mapping between targets and observations which is usually violated in real environments. For instance, a single object can be seen by several observations due to occlusion, or multiple moving objects can be merged into a single observation when moving closely.

In the research, we propose a new data association approach that deals with split/merge nature of object observations. In addition, our approach also tackles ambiguities by taking into account a sequence of observations in a sliding window of frames. To avoid the high computational complexity, a very efficient Markov Chain Monte Carlo (MCMC) technique is proposed to sample and search for the optimum solution in the spatio-temporal solution space. Moreover, various aspects including prior information, object model, motion model and measurement model are explicitly integrated in a theoretically sound framework.

5.1.4. Visual recognition for intelligent vehicles

Participants: Alexandros Makris, Mathias Perrollaz, Christian Laugier.

(a) Camera image, two-way street

(b) Camera image, highway
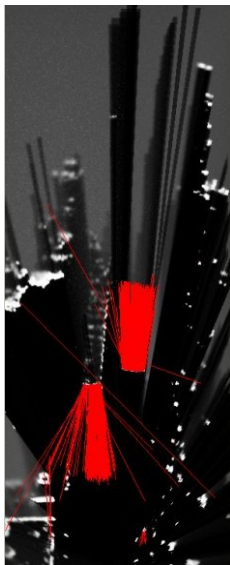
(c) Occupancy and velocity result, two-way street
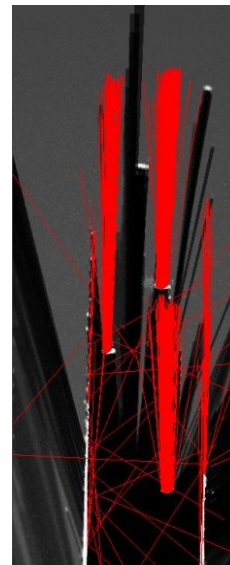
(d) Occupancy and velocity result, highway

Figure 1. Results of the new algorithm : the free cells are black, the occupied ones are white. Unknown areas are grey. When a cell is seen as dynamic, a vector representing the average of the associated motion field is drawn in red.

We have developed an object class recognition method. The method uses local image features and follows the part-based detection approach. It fuses intensity and depth information in a probabilistic framework. The depth of each local feature is used to weigh the probability of finding the object at a given distance. To train the system for an object class, only a database of images annotated with bounding boxes is required, thus automatizing the extension of the system to different object classes. We apply our method to the problem of detecting vehicles from a moving platform. The experiments with a data set of stereo images in an urban environment show a significant improvement in performance when using both information modalities.

In 2013, the method has been published in IEEE Transactions on Intelligent Transportation Systems [14].

5.1.5. Experimental platform for road perception

5.1.5.1. Experimental platform material description

Our experimental platform for road perception is shown in Figure 2. This platform is a commercial Lexus car LS600h equipped with a variety of sensor, including two IBEO Lux lidars placed toward the edges of the front bumper, a TYZX stereo camera plus a high resolution color camera situated behind the windshield, and an Xsens MTi-G inertial sensor with GPS. To do online data computation and data acquisition, a standard computer is located on the back of the car.

This platform allows us to conduct experimentation and data acquisition in various road environments (country roads, downtown and highway), at different time of the day, with various driving situations (light traffic, dense traffic, traffic jams).
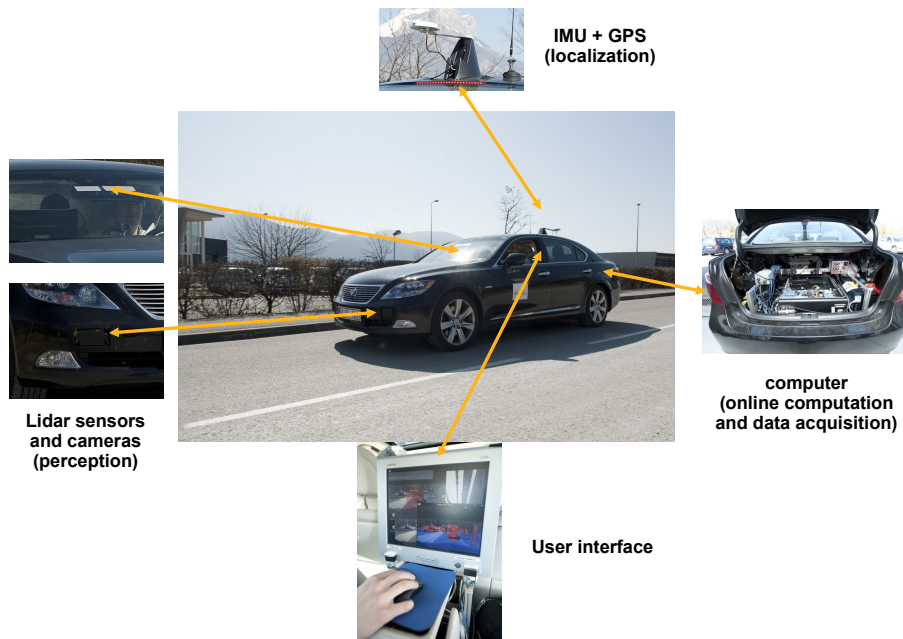

Figure 2. Lexus LS600h car equipped with two IBEO Lux lidars, a stereo plus a monocular camera, and an Xsens MTi-G inertial sensor with GPS.

5.1.5.2. Software architecture

The perception and situation awareness software architecture is integrated in the ROS framework. ROS (http://www.ros.org) is an open source robotics middleware designed to be distributed and modular. For the Lexus platform, we developed a set of ROS module for each sensor and for each perception component. Each perception module can be dynamically connected with the required drivers or other perception modules. The main architecture of the perception components is illustrated on Figure 3.
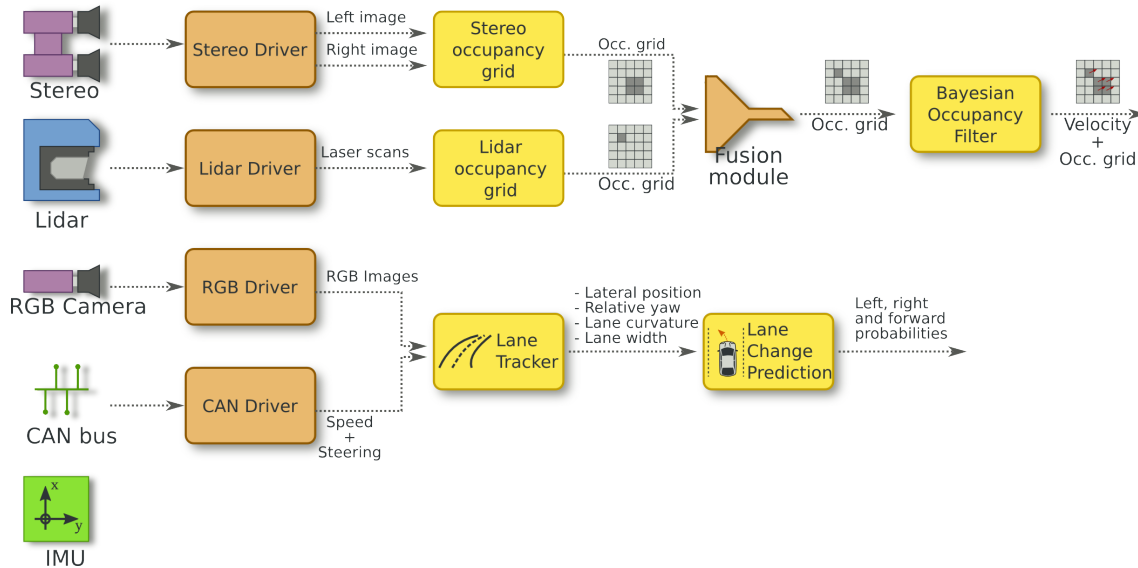

Figure 3. Architecture of the main perception components in the Lexus platform.

5.1.6. *Software and Hardware Integration for Embedded Bayesian Perception*

Participants: Mathias Perrollaz, Christian Laugier, Qadeer Baig, Dizan Vasquez, Lukas Rummelhard, Amaury Nègre.

The objective of this recently started research work is to re-design in a highly parallel fashion our Bayesian Perception approach for dynamic environments (based on the BOF concept), in order to deeply integrate the software components into new multi-processor hardware boards. The goal is to miniaturize the software/hardware perception system (i.e., to reduce the size, the load, the energy consumption and the cost, while increasing the efficiency of the system).

For supported this research, we began to work in the "Perfect" project. This project, included in the IRT-Nano program, involves the CEA-LETI DACLE lab and ST-Microelectronics. Perfect is focusing onto the second integration objectives (6 years) and the development of integrated open platforms in the domain of transportation (vehicle and infrastructure) and in a second step in the domain of health sector (mobility of elderly and handicapped people, monitoring of elderly people at home...). The objective of e-Motion in this project is to transfer and port its main Bayesian perception modules from traditional computing system to embedded low-power multi-processors board. The targeted board is a STHorm from ST Microelectronics which is has a many-core architecture with a very low consumption. In 2013 we worked with the CEA to obtain a first implementation of the Bayesian occupancy grid filter on STHorm. Those preliminary results demonstrated the feasibility of the concepts but highlighted some key points to improve such as the memory footprint we need to reduce to obtain real-time accurate results.
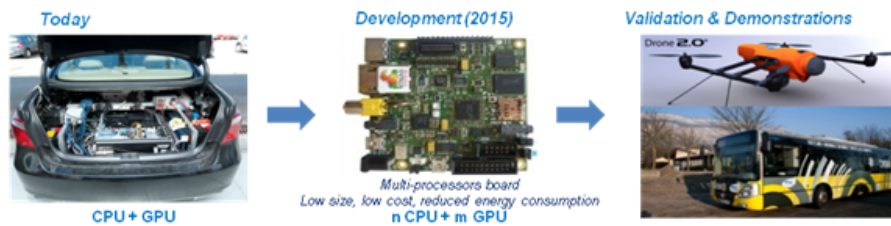
Figure 4. First objective for software/hardware of Bayesian perception : developing and using multiple processor board from mobile technologies. The approach will be validated with real demonstrators..

5.2. Dynamic Change Prediction and Situation Awareness

5.2.1. *Vision-based Lane Tracker*
Participants: Mathias Perrollaz, Amaury Nègre.

In the field of vehicle risk assessment system, vehicle to road localization is an essential information to predict drivers behaviors as well as collision risk evaluation. To achieve this task, we have developed a vision based lane tracker to estimate the geometry of the lane using the line markers. Previous development was based on a Monte-Carlo particle filter to estimate simultaneously the road plane orientation, the lane curvature and the camera position. To perform the particle evaluation, the algorithm first process a ridge extraction of the camera image and then projected the left and right marker line represented by the particle on the ridge image.

The first improvement of the tracker consists on dynamically adapting the scale of the ridge filter to improve the efficiency and the precision of the particle evaluation. The second improvement is capability the perform multi-lane tracking for example in highway environment. To solve this problem, the position of the lane is added to the state and the particle evaluation consider the total number of line marker (a-priori known). Figure 5 shows the results of the lane tracker program on a highway environment.

5.2.2. *Vision-based Lane Change Prediction*
Participants: Suryansh Kumar, Dizan Vasquez, Mathias Perrollaz, Stephanie Lefevre, Amaury Nègre, Maiwen Gault.

For both Advanced Driving Assistance Systems and Autonomous Vehicles, it is very important to have the capability of predicting and understanding the driver's behavior. This work addresses this subject in a bottom-up fashion by first detecting low-level "atomic" maneuvers which can be used as a building block for more complex behavior. Concretely, we have developed a learning-based approach that uses lane tracking data to predict lane changes.

Most works in the literature address this as a classification problem, and often use some version of Support Vector Machines (SVM) to solve it. The problem with this approach is that it is sensitive to noise and can yield high-frequency oscillations in the obtained predictions, moreover, they do not provide any information concerning the Time To Change (TTC). Other approaches use a filtering approaches, using Hidden Markov Models (HMM), for example. Although they produce smoother predictions and, in some cases, even a TTC estimate, some studies [33] suggest that HMM-based approaches are less accurate than those based on SVMs.

Our work combines the advantages of both approaches in a hierarchical fashion. First, lane tracking data (i.e. lane-relative yaw, lane-relative lateral position and their fist-order derivatives) are used as an input of a multi-class SVM. Then, the Bradley-Terry model is used to translate the SVM output into a probability which is used as the observation model of a Bayesian filter (Fig. 6).

(a) Camera image
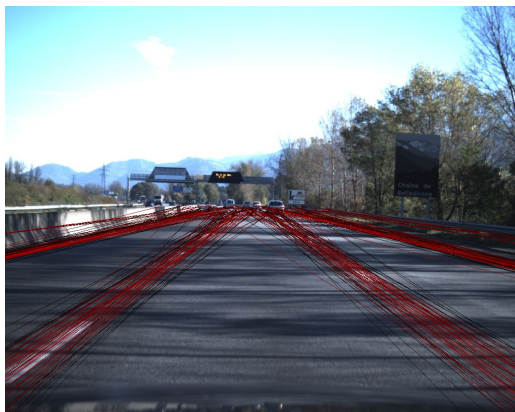
(b) Particles cloud

(c) Lane tracker result

Figure 5. Visual Particle based lane tracking.

HMM   SVM

Figure 6. Overview of our hybrid lane change prediction approach.

This work has been published in the Intelligent Vehicles conference [18]. Since then, we have worked on an improved HMM-only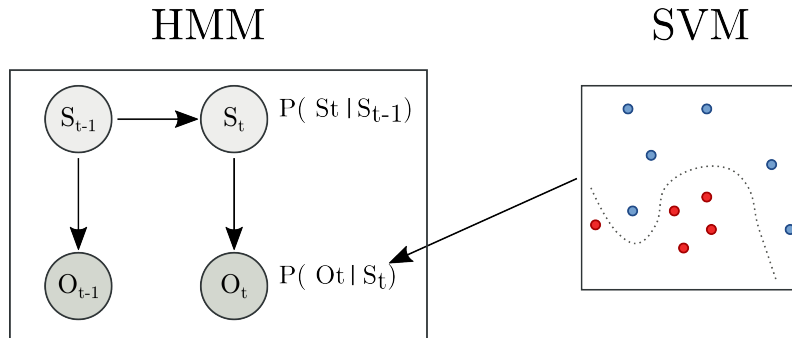 approach which addresses the shortcomings of similar approaches by using a continuous observation model. In our preliminary experiments, this approach leads to improved predictions over the hybrid one.

5.2.3. *Feature-based human behavior modeling*

Participants: Suryansh Kumar, Yufeng Yu, Dizan Vasquez.

When it comes to modeling and learning complex human behavior, the preferred approach in the literature is to try to learn the typical motion patterns that people or vehicles get engaged into in a given environment. This has, however, a major drawback: the learned patterns only apply to the environment where they have been learned. This means that, for a new environment, previous knowledge cannot be used and patterns should be learned from scratch.

This situation has been recently addressed [49] by a family of approaches which rely on two complementary hypotheses:

- *Agents behave like planners*. The idea is that when people or other intelligent agents move around, they plan in order to minimize a cost function. Thus, if this function is known, it fully determines the agent's behavior.

- *The cost is a function of local features*. This extends the previous hypothesis by assuming that the cost function does not only depends on the agent's state but also in a number of external features (e.g. local people density, nearby traffic signs). Since the cost function depends on the features, it is possible to compute it even for previously unseen environments, as long as they contain the same kind of features.

Under these assumptions, the problem becomes that of learning the unknown cost function by observing how people move. This is often called *apprenticeship learning* and, when the underlying planning model is a Markov Decision Process, *inverse reinforcement learning*.

We have been working on a software library and evaluation testbed for different features and cost-function learning algorithms. We have conducted, in collaboration with the University of Freiburg, a first round of experiments concerning people moving in crowds. The results will be the subject of a submission to the IROS 2014 conference.

We have also been working on an application for intelligent vehicles and ADAS. As a first step, we have developed a ROS interface for the TORCS racing simulator, as well as a road simulation using the same platform (Fig. 7). This work has been the product of a collaboration with the Beijing University and IIIT Hyderabad.

Figure 7. The TORCS racing simulator.

5.2.4. *Safety applications at road intersections for connected vehicles*
Participants: Stéphanie Lefèvre, Christian Laugier.

From a safety perspective, road intersections are the most dangerous areas in the road network. They are also the most complex. Because of the extended situational awareness that they provide, wireless vehicular communications (or Vehicle-to-X communications, V2X) could greatly reduce the rate of intersection accidents. However, numerous research challenges remain before the full use of this technology can be achieved. A PhD was started on this topic in 2009 in collaboration with Renault, and was successfully defended in 2012 [42]. The purpose was to formulate and develop a probabilistic reasoning framework which would allow combining the information shared by the vehicles to estimate the situation and the associated risk as a vehicle negotiates an intersection. The first contribution of the PhD was to model the motion of vehicles using a Dynamic Bayesian Network where the maneuvers of different vehicles influence each other via an "expected maneuver". This "expected maneuver" represents what a driver is expected to do given the state of the other vehicles in the area and the traffic rules which apply at the intersection. Thanks to the use of a probabilistic framework, uncertainties related to sensor errors and interpretation ambiguities are handled. The second contribution was a novel approach to risk estimation based on the comparison between what drivers intend to do and what they are expected to do. The reasoning is carried out by performing inference on the Dynamic Bayesian Network introduced earlier, using a particle filter. The approach was validated with field trials using Renault passenger vehicles equipped with vehicle-to-vehicle wireless communication modems [41], and in simulation [40]. The results show that the algorithm is able to detect dangerous situations early and complies with real-time constraints. We also developed a theoretical extension of the model to generalize it to arbitrary traffic situations [29]. This work is still ongoing thanks to an Inria@SiliconValley fellowship granted to S. Lefevre at the end of her PhD. Since January 2013 she is working in the Teleimmersion group at the University of California Berkeley, as a postdoctoral researcher. The research conducted there lead to two new developments on the topic of "Safety applications at road intersections for connected vehicle".
The first development concerns probabilistic decision making for Collision Avoidance (CA) systems. In the processing chain of a CA system, the "Decision making" module follows the "Risk assessment" module. The

research done during the PhD stopped at the "Risk assessment" module, and we now address the challenges present in the "Decision making" module. We identified two main challenges:

1. The first one is that the decision making module has to make decisions based on uncertain knowledge. Sensors provide noisy measurements, digital maps contain errors, and interpreting a vehicle's motion in terms of driver intention is uncertain. These uncertainties propagate to the risk assessment module and to the decision making module, but the latter is still required to make a decision from that uncertain knowledge.

2. The second one is that the timing of interventions is critical. If an intervention is triggered at a time when the uncertainty about the occurrence of a collision is too large, there is a chance that it will end up being a false alarm. High false alarm rates are detrimental to the driver acceptance of safety systems and can lead to the user losing trust in the system. On the other hand, if the system waits until the last moment (certainty about the occurrence of a collision) to trigger an intervention, it might be too late to avoid the accident.

In recent work [20] we proposed to introduce the possibility for a CA system to postpone making a decision. Our objective is to implement the fact that in some situations the new observations obtained by waiting will reduce the uncertainty about the occurrence of a collision, therefore the decision will be more reliable if it is made later using this additional information. The important question to solve is whether the potential gain brought by the additional information outweighs the cost of waiting. In order to answer this question, our decision making approach runs a *preposterior analysis* to determine the expected value and cost of the additional information. The value of the additional information can be quantified by means of the Expected Value of Sample Information (EVSI). It corresponds to the additional expected payoff possible through knowledge of the additional information and is computed by subtracting the expected costs of deciding with and without additional information. The cost of the additional information is quantified by means of the Expected Cost of Waiting (ECW). It is computed as the difference between the probability that the CA system will be able to avoid the potential collision if it intervenes now and if it intervenes at time t+1. Our decision making strategy is to postpone the decision making process to time t+1 if and only if the EVSI is positive and the ECW is null. The algorithm was tested in simulation at a two-way stop intersection for collision scenarios and no-collision scenarios involving two vehicles. A comparative evaluation with a decision making strategy which does not allow postponing decisions showed that our approach generates fewer false alarms and avoids as many collisions. These results were published at the conference IEEE IROS'13 [20] and a patent application was filed with UC Berkeley [32].

The second development addresses the relationship between privacy strategies for V2X and safety applications which rely on V2X. User privacy is a requirement for wireless vehicular communications, and a number of privacy protection strategies have already been developed and standardized. In particular, methods relying on the use of temporary pseudonyms and silent periods have proved their ability to confuse attackers who would attempt to track vehicles. However, these privacy protection schemes are not without consequences for safety applications. Such applications make decisions (e.g. warning drivers of an upcoming danger) based on their current estimation of the state of the real world, and this representation is created from the information contained in beacons received from other vehicles. Therefore, interruptions in the transmission of information will impact the decision-making process. If a silent period is scheduled to start at a safety-critical moment, it could result in safety systems not intervening when they should have, namely a "missed intervention". From a user and safety perspective, this is not acceptable. In this work we address this issue and evaluate the impact of pseudonym change strategies on V2X-based Intersection Collision Avoidance (ICA) system. We use the ICA system developed during the PhD and simulated 3 different privacy protection strategies:

1. The "*Fixed ID*" strategy assigns a fixed pseudonym to a vehicle for the entire duration of a trip (i.e. a new pseudonym is assigned to the vehicle every time it starts). Testing this case gives us a reference for how well the collision avoidance system performs when there is no pseudonym change and no silent period during a trip, which is what was assumed in our PhD work.

2. The "*Baseline*" strategy follows the recommendations of the SAE J2735 standard for V2X communications. Pseudonyms are changed every 120 seconds and are followed by a silent period of random duration.

3. The "*Adaptive*" strategy is a modified version of the *Baseline* strategy where the risk of the situation is taken into account to decide whether or not a vehicle should be allowed to change pseudonym at time t. It relies on the estimation of the current ability of the collision avoidance system to keep the vehicle on a collision-free trajectory. The idea here is to authorize a pseudonym change and silent period only if it will not affect the performance of the safety application.

Simulations were conducted using the same simulator and the same scenarios as the tests run during the PhD. The performance of the three privacy strategies was evaluated both in terms of privacy and in terms of successful interventions of the ICA system. The results show that the ICA application requires silent periods to be shorter than two seconds in order to operate correctly in conjunction with the SAE J2735 standard. They also indicate that the addition of simple rules which authorize or not a pseudonym change depending on the context leads to major safety improvements compared to the SAE J2735 standard alone (see Figure 8). These results, which were published at the conference IEEE VNC'13 [21], highlight the necessity of a joint design. That is, the requirements of safety applications should be taken into account when designing privacy strategies, and pseudonym change schemes should be accounted for when designing safety applications which rely on V2X communications. This collaboration is necessary in order to ensure that vehicular communications and safety applications do not neutralize each other, but instead, work together toward safer roads.
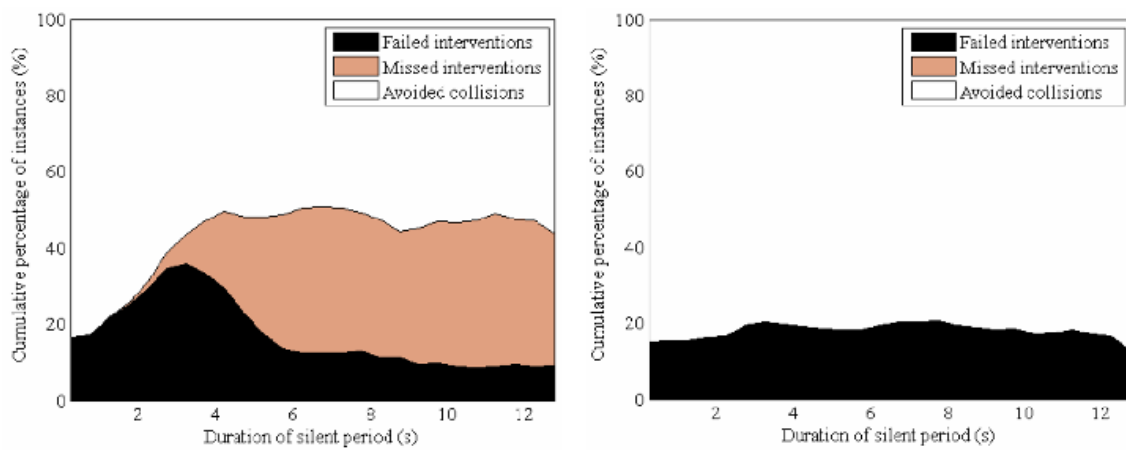
Figure 8. Percentage of missed interventions, avoided collisions, and failed interventions as a function of the duration of the silent period for the Baseline strategy (left) and the Adaptive strategy (right).

5.2.5. *Guidance for Uncertain shooting domain*

Participant: Emmanuel Mazer.

This study is made in collabortion with MBDA (Monsieur Le Menec) and Probayes (Monsieur Laurent Saroul) under the ITP framework financed by the british MOD and the french DGA.

From N°51 of Vector Magazine (copyright MBDA) *It's an enduring question facing those in military conflict: 'when do you pull the trigger?' However, for pilots in air combat there is an added question: 'Once you've pulled the trigger, when do you break the link with your missile?' A new answer to that problem was a highlight of the MCM-ITP conference at Lille in May (see Vector 50). Entitled 'Guidance in Uncertain Shooting Domains', this joint project between MBDA and French company Probayes has produced a set of algorithms to help a pilot decide when to break a telemetry link. It's a decision fraught with danger. As pilots approach a target, the longer they keep the link, the greater the chance of their missile finding its target. However, closing*

in on the target usually means entering the enemy's own kill zone. So, a calculation of the best trade-off between mission success and pilot safety needs to be made.

"At the moment, when a pilot is engaging an enemy aircraft, he's obliged to do sums in his head," explained Graham Wallis, MBDA UK's Chief Technologist. "What we're trying to do is to take that away, and hide it behind a probability display." The problem arises because a seeker's scanning range is often far shorter than the maximum travelling distance, or kinematic range, of a missile. Though less of an issue at short range, it's a problem for medium-range weapons – where the target is likely to manoeuvre beyond the initial seeker scan area; hence the need for guidance from the pilot, who may have the target in radar sight.

SUCCESS PROBABILITY Stepping back, there are two sides to the firing equation. As customers require an air-to-air missile that will find its target almost 100 of the time, MBDA provides distance data (known as Launch Success Zone tables) to achieve that. They are understandably conservative. Clearly, though, the final decision to break the datalink can only be taken by the pilot, who is also making mental calculations to minimise his or her exposure to deadly risk. GUSD effectively offers a 'probability meter' to help reconcile those two imperatives.

Physically, GUSD could be a display with four bars and the circle of a pie-chart. Each bar represents the probability in percentage terms of an enemy pilot adopting one of four typical behaviours during air combat: flying head-on to attack; turning tail and heading for home, and either turning left or right – along with the probabilities that the enemy has just launched its own missile. The pie chart gives a single percentage – of the MBDA missile's chances of hitting its target. "The figures displayed are effectively our computer trying to read the mind of the enemy pilot," said Graham Wallis, whose team also drew on the experience of MBDA's former air force pilots.

QUICK CALCULATIONS Not surprisingly, the computations behind GUSD are hugely complex. The main input is the realtime radar tracking data of the enemy aircraft, although other elements such as seeker acquisition data, missile dynamics and the missile's inertial navigation errors are also included. A set of algorithms (and their associated mathematical methods, see box) then process this input – with the three key algorithms covering target behaviour and identification (Hidden Markov Models); the generation of bundles of trajectories (Markov Chains and Monte Carlo techniques) and trajectory collision checking (R-Tree).

Currently at Technology Readiness Level 3, GUSD's future depends on being incorporated into a programme. The generic data used to date would be replaced by real missile and seeker data, requiring GUSD to move out of the open forum of MCM-ITP and into the area covered by defence secrecy. "Implementation of research and technology is particularly difficult when it comes to jet fighters," Graham Wallis declared. "But I'm optimistic it will get into a future upgrade of current aircraft, and could even replace the Launch Success Zone tables as a firing cue for pulling that trigger."

MATHEMATICAL MODELS Named after 19th century Russian mathematician Andrey Markov, the Markov Chain uses a set of rules to predict what will happen next in a situation, when all the variables are known. In a game of bridge, if all the hands were known to all players and they had no discretion over which card to play next, every card laid down could be predicted as a Markov Chain. With a Hidden Markov Model, a player doesn't know what an opponent holds but can infer that, for example, they no longer have any trump cards because of how they have played their last hand. The Model takes multiple states e.g. 'Opponent Has Trumps' or 'Opponent Doesn't Have Trumps' and establishes a percentage weighting of probability to each – which can then be used for a decision over the best card to play. Though it is only an analogy, GUSD's algorithms use the mass of input data to infer the probability of an enemy pilot's tactical moves. R-trees are a way of handling multi-dimensional information - in GUSD's case by using geometric models that drastically cut the computation load.

OTHER APPLICATIONS Even before its own future is decided, GUSD could already lead to a successor MCM-ITP project with Probayes in the area of mission planning for long-range missiles. Called Rapid Mission Planning and Rehearsal, it could automate much of what is currently a labour-intensive process and to provide the customer with different options for mission routes – each with its own probability rating for success.

Figure 9. artistic view of GUSD (copyright MBDA)

5.3. Human Centered Navigation in the physical world

5.3.1. *Social Mapping*

Participants: Panagiotis Papadakis, Anne Spalanzani, Christian Laugier.

With robots technology shifting towards entering human populated environments, the need for augmented perceptual robotic skills emerges that complement to human presence. In this integration, perception and adaptation to the implicit human social conventions plays a fundamental role. Toward this goal, we introduce a novel methodology to detect and analyse complex spatial interactions of multiple people and encode them in the form of a social map, whose structure is obtained by computing a latent space representation of human proxemic behaviour. We accomplish this by appointing to humans distinct, skew-normal density functions that quantify social sensitivity and by using them in the sequel to induce a training set for regressing a collective density function of social sensitivity (see fig. 10). Finally, we extract level-sets of constant social sensitivity levels within the social map by which we can effectively and efficiently analyse individual as well as shared interaction zones of varying shape and size. Extensive experiments on human interaction scenarios demonstrate the feasibility and utility of the proposed approach in diverse conditions and promote its application to social mapping of human-populated environments. This work was published at IROS [23] and submitted to RAS journal.

5.3.2. *Goal oriented risk based navigation in dynamic uncertain environment*

Participants: Anne Spalanzani, Jorge Rios-Martinez, Arturo Escobedo-Cabello, Procopio Silveira-Stein, Gregoire Vignon, Alejandro Dizan Vasquez Govea, Christian Laugier.

Navigation in large dynamic spaces has been adressed often using deterministic representations, fast updating and reactive avoidance strategies. However, probabilistic representations are much more informative and their use in mapping and prediction methods improves the quality of obtained results. Since 2008 we have proposed a new concept to integrate a probabilistic collision risk function linking planning and navigation methods with the perception and the prediction of the dynamic environments [36]. Moving obstacles are supposed to move along typical motion patterns represented by Gaussian Processes or Growing HMM. The likelihood of the obstacles' future trajectory and the probability of occupation are used to compute the risk of collision. The proposed planning algorithm, call RiskRRT (see Figure 11 for an illustration), is a sampling-based partial planner guided by the risk of collision. Results concerning this work were published in [37] [38] [39]. [47]
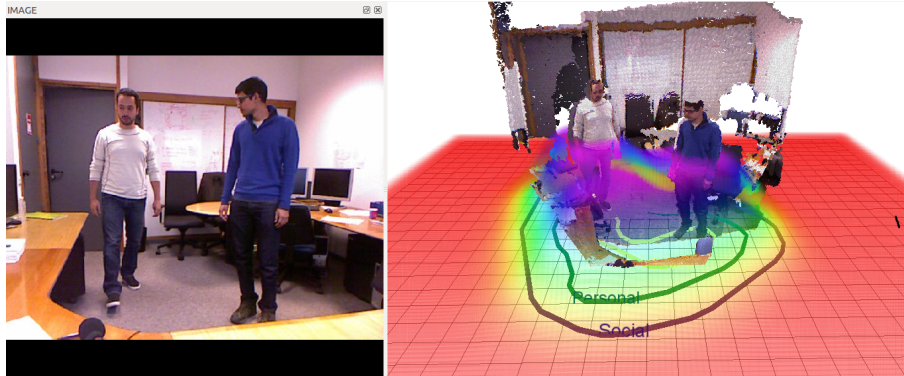
Figure 10. A representative example of mapping human social interactions using the proposed methodology. The regressed global sociality density along with isocontours of constant social comfort are superimposed on the corresponding scene.

and [48]. In 2013, Jorge Rios defended his phD on this topic. We obtained an Inria ADT to optimize and share the RiskRRT algorithm.
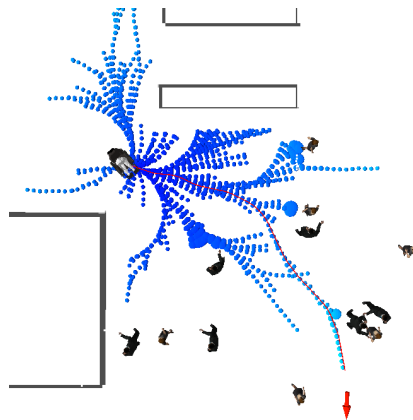
Figure 11. Social navigation example. RiskRRT selected a plan (red line) to the goal (red arrow).

5.3.3. Navigation Taking Advantage of Moving Agents

Participants: Procopio Silveira-Stein, Anne Spalanzani, Christian Laugier.

In this work, we proposes a different form of robotic navigation in dynamic environments, where the robot takes advantage of the motion of pedestrians, in order to improve its own navigation capabilities. The main idea is that, instead of treating persons as dynamic obstacles that should be avoided, they should be treated as special agents with an expert knowledge of navigating in dynamic scenarios. To benefit from the motion of pedestrians, this work proposes that the robot select and follow them, so it can move along optimal paths, deviate from undetected obstacles, improve navigation in densely populated areas and increase its acceptance by other

humans. To accomplish this proposition, novel approaches are developed in the area of leader selection, where two methods are explored. The first uses motion prediction approaches while the second uses a machine learning method, to evaluate the leader quality of subjects, which is trained with real examples. Finally, the leader selection methods are integrated with motion planning algorithms and experiments are conducted in order to validate the proposed techniques. One of the most relevant application is navigation among crowds. Figure 12 illustrates the concept.

Figure 12. Navigation among crowds. The robot (rectangle) needs to reach the right side of the corridor. 2 groups of people (one in yellow, the other in blue) are crossing in this corridor. A classical motion planning would not find a path. The robot choses a leader (represented by a green circle around a person) and follows him.

The work is published in [25] [24] and Procopio Stein defended his phD the 11th of december 2013 at the Aveiro University (phD co-directed by Anne Spalanzani and Vitor Santos).

5.3.4. *Autonomous Wheelchair for Elders Assistance*

Participants: Arturo Escobedo-Cabello, Gregoire Vignon, Anne Spalanzani, Christian Laugier.

The aging of world's population is bringing the need to provide robotic platforms capable to assist elder people to move [46]. It is necessary that such transportation is reliable, safe and comfortable. People with motor disabilities and elders are expected to benefit from new developments in the field of autonomous navigation robotics.

Autonomously driven wheelchairs are a real need for those patients who lack the strength or skills to drive a normal electric wheelchair. The services provided by this kind of robots can also be used to provide a service of comfort, assisting the user to perform difficult tasks as traversing a door, driving in a narrow corridor etc.

Simple improvements of the classical powered wheelchair can often diminish several difficulties while driving. This idea of comfort has emerged as a design goal in autonomous navigation systems, designers are becoming more aware of the importance of the user when scheming solution algorithms. This is particularly important when designing services or devices intended to assist people with some disability. In order for the robot to have a correct understanding of the intention of the user (when moving around) it is necessary to create a model of the user that takes into account his habits, type of disability and environmental information. The ongoing research project is centered in the understanding of the intentions of the user while driving an autonomous wheelchair, so that we can use this information to make this task easier.

During the last two years the work was centered in the improvement of the usability of the system. A review of the state of the art in user's intention estimation algorithms was made and a new model to infer the intentions of the user in a known environment was presented [34], [35].

The algorithm models the intention of the user as 2D topological goals in the environment. Those places are selected according to how frequently they are visited by the user (user habits). The system was designed so that the user can give orders to the wheelchair by using any type of interface, as long as he can show the direction of the intended movement (joystick, head tracking, brain control, etc). As shown in figure 13, the chosen approach uses a Dynamic Bayesian Network to model and infer the intentions. The main contribution of this work is to model the intention of the user as topological goals instead of normal trajectory-based methods, therefore the model is simpler to deal with.

In 2013 the results of the user intention destination method were published in the IROS conference [16]. The presented work covered the following aspects:
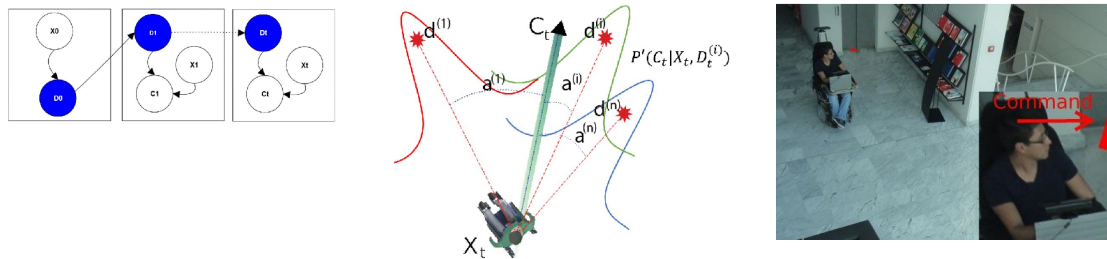
Figure 13. User's Intention Estimation Algorithm Left:User's intention model. The Bayesian network used to estimate the current user's intended; Center: The probability value for a given command C_t (big arrow) is proportional to the angle a_i formed respect to each goal g_i in the environment. Right: The user is looking to the left (in the direction of his desired goal). Once that the user's intention estimation system computes the goal with the highest probability, the autonomous navigation module plans the path and controls the movement of the wheelchair to take the user to the destination.

User Intention Estimation: Two different methods to drive the wheelchair were compared, a semi-autonomous and a manual mode. In semi-autonomous mode the user's intention is estimated from the position of the face and the wheelchair takes care of all the planning to arrive there while avoiding obstacles. In manual mode the wheelchair is driven using the face without assistance from the robotic controller.

The Bayesian estimator shown in Fig.13 was used to do the inference of the desired destination of the user in semi-autonomous mode. The user's intention was modeled as a set of destinations commonly visited by the user and the task consisted in finding the destination targeted by the user.

Interfaces: People with motor disabilities and elders often have problems using joysticks and other standard control devices. Under this consideration our experimental platform was equipped with different types of user-interfaces to provide a multi-modal functionality as described in [35]. A face pose interface allows to control the wheelchair's motion by changing the face direction, while voice recognition interface is used to guarantee an adequate control of the wheelchair for those commands that otherwise would be difficult to give by only using the face (Stop, start, etc). This exploitation of more natural and easy-to-use human machine interfaces was one of the main contributions of the work presented in [16].

Experimental evaluation: Experiments were done in the hall of the Inria Rhône-Alpes laboratory. People in the scene were tracked to detect the most visited destinations in this setting (red circles). Those typical destinations were then placed in the map used by the robotic wheelchair. Each destination has a probability value related to the number of times that it is visited by people. The extracted typical destinations and related probabilities are used as prior knowledge when inferring the user's desired destination. In Fig.14(Right) the spheres represent the typical destinations placed in the internal map o the wheelchair and the size of the sphere represents the probability of being the desired destination of the user in the wheelchair given it's position in the map and direction of the face (blue arrow).

To evaluate the performance of the method different persons were asked to drive the wheelchair in both "manual" and "semi-autonomous" mode. The trajectories of followed by the wheelchair were recorded and evaluated in [16], In Fig.15 one sample of those trajectories is presented where it can be appreciated how those trajectories executed with assistance of the robot are considerably softer than those obtained in manual mode as explained in [16].

Human aware navigation: Current work is being done in the construction of a social cost-map that is able to work with different open source path planning algorithms. This plug-in was developed using the method presented by Rios in [45].
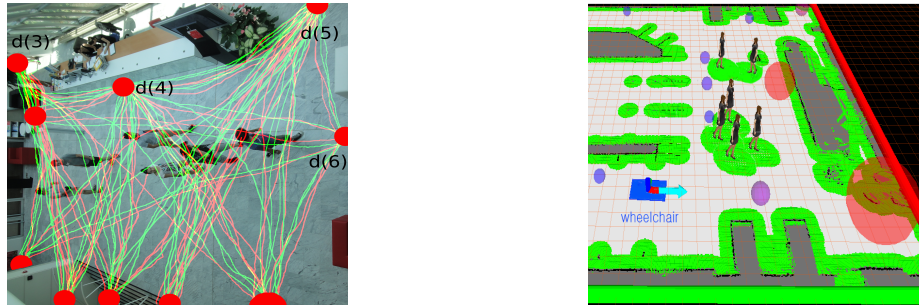
Figure 14. Left: The users of a normal environment move between typical destinations that can be learned. Right: The typical destinations marked in the map used by the wheelchair, The probability for each destination given the position of the wheelchair and direction of the command is proportional to the size of the sphere.
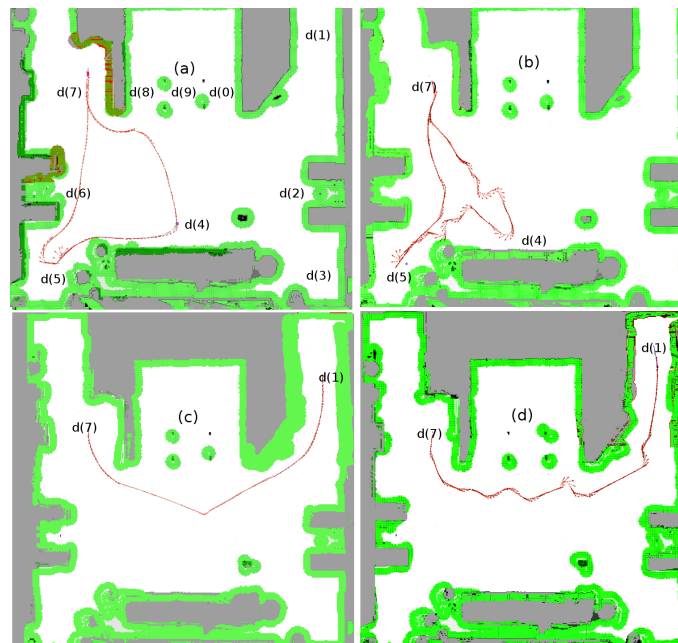
Figure 15. Experimental evaluation of the user's intention method. Some samples of the resulting trajectories are presented. (a) and (c) show the results when using the assistance of the user's intention estimation system. (b) and (d) were achieved by driving the wheelchair using the face without any assistance. Here we can it can be appreciated how those trajectories executed with assistance of the robot are considerably softer than those obtained in manual mode.

5.3.5. *Bayesian modelling to implement and compare different theories of speech communication*

Participants: Raphael Laurent, Pierre Bessière, Julien Diard, Jean-Luc Schwartz.

A central issue in speech science concerns the nature of representations and processes involved in communication. The search for phoneme or syllable specific invariants led to three major sets of approaches: motor, auditory and perceptuo-motor theories. They have been widely argued for and against, but the theoretical debate appears to be stagnating. It is our belief that computationnal models designed within a rigorous mathematical framework may allow to put forward new arguments to support either theory, and new ideas for experiments to be carried out on human subjects.

We have designed an integrative Bayesian model which allows to study auditory, motor and perceptuo-motor aspects of speech production and perception. This model was tested on perception tasks on evaluation corpora with more and more variability compared to the learning corpus. This showed a really high robustness of the purely motor model, which contained more information that it is the case in practise, due to unrealistic learning methods. The work was then focused on more realistic learning algorithms, where speech motor gestures are unsupervisedly learned through imitation, by generating motor gestures trying to reach auditory targets, and memorising the acoustics corresponding to these motor commands. This work was published in 2013 [19]. Raphael Laurent defended his phD in 2013.

5.3.6. *Bayesian computing*

Participants: Emmanuel Mazer, Pierre Bessière.

A book and the compagnon software on bayesian programming have been released this year :

The book "Bayesian Programming" is available at http://www.crcpress.com/product/isbn/9781439880326 and the associated software at http://www.probayes.com/fr/Bayesian-Programming-Book/

Features

Presents a new modeling methodology and inference algorithms for Bayesian programming Explains how to build efficient Bayesian models Addresses controversies, historical notes, epistemological debates, and tricky technical questions in a dedicated chapter separate from the main text Encourages further research on new programming languages and specialized hardware for computing large-scale Bayesian inference problems Offers an online Python package for running and modifying the Python program examples in the book

Summary

Probability as an Alternative to Boolean Logic While logic is the mathematical foundation of rational reasoning and the fundamental principle of computing, it is restricted to problems where information is both complete and certain. However, many real-world problems, from financial investments to email filtering, are incomplete or uncertain in nature. Probability theory and Bayesian computing together provide an alternative framework to deal with incomplete and uncertain data.

Decision-Making Tools and Methods for Incomplete and Uncertain Data

Emphasizing probability as an alternative to Boolean logic, Bayesian Programming covers new methods to build probabilistic programs for real-world applications. Written by the team who designed and implemented an efficient probabilistic inference engine to interpret Bayesian programs, the book offers many Python examples that are also available on a supplementary website together with an interpreter that allows readers to experiment with this new approach to programming.

Principles and Modeling

Only requiring a basic foundation in mathematics, the first two parts of the book present a new methodology for building subjective probabilistic models. The authors introduce the principles of Bayesian programming and discuss good practices for probabilistic modeling. Numerous simple examples highlight the application of Bayesian modeling in different fields.

Formalism and Algorithms

The third part synthesizes existing work on Bayesian inference algorithms since an efficient Bayesian inference engine is needed to automate the probabilistic calculus in Bayesian programs. Many bibliographic references are included for readers who would like more details on the formalism of Bayesian programming, the main probabilistic models, general purpose algorithms for Bayesian inference, and learning problems.

FAQs Along with a glossary, the fourth part contains answers to frequently asked questions. The authors compare Bayesian programming and possibility theories, discuss the computational complexity of Bayesian inference, cover the irreducibility of incompleteness, and address the subjectivist versus objectivist epistemology of probability.

The First Steps toward a Bayesian Computer A new modeling methodology, new inference algorithms, new programming languages, and new hardware are all needed to create a complete Bayesian computing framework. Focusing on the methodology and algorithms, this book describes the first steps toward reaching that goal. It encourages readers to explore emerging areas, such as bio-inspired computing, and develop new programming languages and hardware architectures.
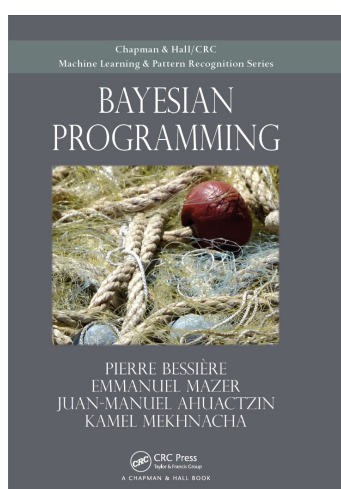
Figure 16. Bayesian Programming book covert

6. Bilateral Contracts and Grants with Industry

6.1. Bilateral Contracts with Industry

6.1.1. *Toyota Motors Europe*

[Feb 2006 - Feb 2009] [Dec 2010 - Dec 2014]

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.

6.1.2. Renault

[Jan 2010 - Feb 2013]

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

6.1.3. PROTEUS

[November 2009 - October 2013]

PROTEUS ("Robotic Platform to facilitate transfer between Industries and academics") is an ANR project involving 6 industrial and 7 academic partners. This projects aims to develop a software platform which helps to share methods and softwares between academics and industries in the field of mobile robotics.

The project works on three main aspects :

- Specification of different scenarios and its associated formalism.
- Definition of a domain specific language (DSL) to specify and execute the given scenarios.
- Setting up 4 robotic challenges to evaluate the capacity and the usability of the platform.

The contribution of *e-Motion* to PROTEUS is first to provide its expertise on mobile robotics to develop the DSL and next to provide a simulation environment with its platform "CycabTK".

Juan Lahera-Perez has been recruited as engineer to work on this project with Amaury Nègre.

6.1.4. 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).

6.2. Bilateral Grants with Industry

A Postdoc in Collaboration with the University of California Berkeley, Inria and Renault (Inria@SiliconValley fellowship) started in January 2013 on the topic of "Safety applications at road intersections for connected vehicle".

6.3. National Initiatives

6.3.1. Inria Large Initiative Scale PAL (Personaly Assisted Living)

[Nov 2010 - Nov 2014]

The objective of this project is to create a research infrastructure that will enable experiments with technologies for improving the quality of life for persons who have suffered a loss of autonomy through age, illness or accident. In particular, the project seeks to enable development of technologies that can provide services for elderly and fragile persons, as well as their immediate family, caregivers and social groups.

The Inria Project-Teams (IPT) participating in this Large-scale initiative action Personally Assisted Living (LSIA Pal) propose to work together to develop technologies and services to improve the autonomy and quality of life for elderly and fragile persons. Most of the associated project groups already address issues related to enhancing autonomy and quality of life within their work programs. This goal of this program is to unite these groups around an experimental infrastructure, designed to enable collaborative experimentation.

Working with elderly and fragile to develop new technologies currently poses a number of difficult challenges for Inria research groups. Firstly, elderly people cannot be classified as a single homogeneous group with a single behavior. Their disabilities may be classified as not just physical or cognitive, motor or sensory, but can also be classified as either chronic or temporary. Moreover, this population is unaccustomed to new technologies, and can suffer from both cognitive and social inhibitions when confronted with new technologies. None-the-less, progress in this area has enormous potential for social and financial impact for both the beneficiaries and their immediate family circle.

The spectrum of possible actions in the field of elderly assistance is large. We propose to focus on challenges that have been determined through meetings with field experts (medical experts, public health responsible, sociologists, user associations...). We have grouped these challenges into four themes: monitoring services, mobility aids, transfer and medical rehabilitation, social interaction services. These themes correspond to the scientific projects and expectations of associated Inria projects. The safety of people, restoring their functions in daily life and promoting social cohesion are all core motivations for this initiative.

e-Motion concentrates his work on mobility aids using the wheelchair.

6.3.2. ADT P2N

[Oct 2013 - Sept 2015]
The ADT P2N (Autonomous Navigation: From Perception to Navigation) involving e-Motion and Lagadic was accepted in 2012 for Lagadic and extended to emotion (with an IJD) in 2013. The ADT is dedicated to the development of a common software integrating perception and navigation methods developed in both teams. Demos will be done on various mobile robotic platforms such as wheelchairs, caddy...

7. Partnerships and Cooperations

7.1. European Initiatives

7.1.1. FP7 Projects

European Project (Strep) Bambi (Bottom-up Approaches to Machines dedicated to Bayesian Inference). The Bambi project started January 1st 2014 for a period of three years. The participant to this project are CNRS, HUJI (ISRAEL), ULG (Belgique), ISR(Portugal) ProbaYes(France). We propose a theory and a hardware implementation of probabilistic computation inspired by biochemical cell signaling. We will study probabilistic computation following three axes: algebra, biology, and hardware. In each case, we will develop a bottom-up hierarchical approach starting from the elementary components, and study how to combine them to build more complex systems. We propose Bayesian gates operating on probability distributions on binary variables as the building blocks of our probabilistic algebra. These Bayesian gates can be seen as a generalization of logical operators in Boolean algebra. We propose to interpret elementary cell signalling pathways as biological implementation of these probabilistic gates. In turn, the key features of biochemical processes give new insights for new probabilistic hardware implementation. We propose to associate conventional electronics and novel stochastic nano-devices to build the required hardware elements. Combining them will lead to new artificial information processing systems, which could, in the future, outperform classical computers in tasks involving a direct interaction with the physical world. For this purpose, this project associates research in Bayesian probability theory, molecular biology, nanophysics, computer science and electronics. The e-motion team is mainly concerned by : The development of Stochastic temporal coding of probabilistic information and the adaptation and learning in probabilisitc machines

7.1.2. Major European Organizations with which you have followed Collaborations

Department of Electrical & Computer Engineering: University of Thrace, Xanthi (GREECE)

Subject: 3D coverage based on Stochastic Optimization algorithms

BlueBotics: BlueBotics Company, Lausanne (Switzerland)

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

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.

Universidade de Aveiro (Portugal)

Subject: Leader following. Co-directed phD.

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

Subject: Target interception.

Social Robotics Laboratory, Freiburg (Germany)

Subject: Human behavior understanding.

7.2. International Initiatives

7.2.1. "PRETIV"

[November 2011- October 2014]
Multimodal Perception and REasoning for Transnational Intelligent Vehicles" (PRETIV) is a three-year ANR project accepted in the framework of the Blanc International II Programme with participants from France (e-Motion of Inria, Heudiasyc of CNRS, PSA Peugeot Citroen DRIA in Velizy) and China (Peking University, PSA Peugeot Citroen Technical Center in Shanghai). The project aims at developing of an online multimodal perception system for a vehicle and offline reasoning methods, dealing with incompleteness and uncertainties in the models and sensor data, as well as at conducting experiments in typical traffic scenarios in France and China to create an open comparative dataset for traffic scene understanding. The perception system will incorporate vehicle localization, mapping of static environmental objects, detecting and tracking of dynamic objects in probabilistic frameworks through multimodal sensing data and knowledge fusion. The reasoning methods are based on sensor data to learn semantics, activity and interaction patterns (vehicle - other objects, vehicle - infrastructure) to be used as a priori information to devise effective online perception algorithms toward situation awareness. The comparative dataset will contain experimental data of typical traffic scenarios with ground-truth, which will be used to learn country-specific traffic semantics and it will be open to the public.

7.2.2. Visits of International Scientists

Mario Garzon, phD at Universidade de Madrid was in our team from february 2013 to april 2013.

7.2.3. Inria International Labs

7.2.3.1. "iCeiRA"
[Jan 2013- Jan 2018] The e-Motion project-team has won (in cooperation with the CNRS laboratories LAAS and ISIR) a major partnership with Taiwan in the scope of the call "International Excellence Laboratories" (I-RiCE program) launched by the National Science Council (NSC) of Taiwan. The laboratory is hosted by the National University of Taiwan, it is supported for 5 years, and the collaborative research is focusing on Human centered Robotics.

7.2.4. Participation In other International Programs

7.2.4.1. "ict-PAMM"

[September 2011 - September 2013]
ict-PAMM is an ICT-ASIA project accepted in 2011 for 2 years. It is funded by the French Ministery of Foreign Affair and Inria. This project aims at conducting common research activities in the areas of robotic mobile service and robotic assistance of human in different contexts of human life. French partners are Inria-emotion from Grenoble, Inria-IMARA from Rocquencourt and Institut Blaise Pascal from Clermont-Ferrand. Asian Partners are IRA-Lab from Taiwan, ISRC-SKKU from Suwon in Korea, ITS-Lab from Kumamoto in Japan and Mica Institute from Hanoi in Vietnam.

7.2.4.2. "Predimap"

[September 2011 - September 2013]
Predimap is an ICT-ASIA project accepted in 2011 for 2 years. It is funded by the French Ministery of Foreign Affair and Inria. This project aims at conducting common research activities in the area of perception in road environment. The main objective is the simultaneous use of local perception and Geograpical Information Systems (GIS) in order to reach a global improvement in understanding road environment. Thus the research topics included in the project are: local perception, precise localization, map-matching and understanding of the traffic scenes. French partners are Inria-emotion from Grenoble, Heudiasyc team from CNRS/UTC, and Matis team from IGN. Foreign partners are Peking University and Shanghai Jiao Tong University in China, CSIS lab from Tokyo University in Japan and AIT Geoinformatics Center in Thailand.

7.3. International Research Visitors

7.3.1. Visits to International Teams

- In relation with the Bambi project, Emmanuel Mazer visited Dr. Vickash Masinghka at the Mit Computer science department to establish an academic collaboration around probabilistic computation (Bambi Project). On the same subject but more related to the industrial side, Emmanuel Mazer visited the research center of AMAZON in Berlin and the Microsoft research center in Cambridge to evaluate future collaboration.
- Chiara Troiani spent 6 month at the University of Zurich, in the Robotics and Perception Group (Switzerland).
- Gregoire Vignon spent 2 month at the iCeiRA lab (Taiwan).

8. Dissemination

8.1. Scientific Animation

- C. Laugier is Guest Editor (with A. Zelinsky, A. Broggi and U. Ozgüner) for the chapter "Intelligent Vehicles" of the 2nd edition of the Springer "Handbook of Robotics" to be published in April 2014.
- C. Laugier is Guest Editor (with Ph. Martinet and U. Nunes) for a Special Issue on "Perception and Navigation for Autonomous vehicles" of the IEEE Robotics and Automation Magazine. This issue will be published in March 2014.
- A. Spalanzani co-organised a workshop on Assistance and Service robotics in a human environment during IROS'13, Tokyo, Japan.
- A. Spalanzani co-organised a workshop on Wireless Communications and User centered Services in Pervasive Environments 2013, Hanoi, Vietnam, in the scope of Saisons croisées France-Vietnam.
- A. Spalanzani was associate editor of the Ro-Man 2013 conference.
- C. Laugier co-organized (with Ph. Martinet, U. Nunes, and C. Stiller) the 5th Workshop on "Planning, Perception and Navigation for Intelligent Vehicles" at the IEEE/RSJ IROS 2013 conference, Tokyo, November 2013.

- C. Laugier was co-chair (with Prof. Nobuki Murayama) of the workshop on ICT-PAMM, Kumamoto (Japan), Nov. 2013.
- C. Laugier was a member of the International Program Committee of the IEEE/RSJ IROS 2013 conference. He was also an Associate Editor for IROS 2013.
- C. Laugier was an Associate Editor for the IEEE ICRA 2013 conference.
- C. Laugier, A. Spalanzani, P.B. Wieber co-organized (with J. Troccaz from TIM-C and N. Simeon from LAAS) the 9th JNRR (French "Journée Nationale de la Recherche en Robotique ") in Annecy (France), 15-18 October 2013.
- C. Laugier and M. Perrollaz co-organized with Philippe Broun and the Inria In'Tech team in Grenoble, the in'Tech Seminar on "Perception embarquée pour les véhicules de demain", Inria Grenoble Rhône-Alpes, October 24th 2013.
- C. Laugier was the scientific coordinator for the Inria Robotics Evaluation Seminar, March 2013.
- C. Laugier is co-chair (with Ph. Martinet and C. Stiller) of the IEEE RAS Technical Committee on "Autonomous Ground Vehicles and Intelligent Transportation Systems".
- C. Laugier is a member of the Advisory / Steering Committee of IEEE/RSJ IROS conference.

8.2. Teaching - Supervision - Juries

8.2.1. Teaching

- International Master 2 MOSIG-INP, Course on "Autonomous Robots" (24 h), C. Laugier (responsible), A. Martinelli, M. Perrollaz, A. Nègre. Grenoble University, France.
- C. Laugier and A. Spalanzani have given a tutorial on "Autonomous Robotics" at the ISIE 2013 Conference, Taipei, May 2013.
- Master CNAM: "Basic technologies for autonomous Robotics", C. Laugier, CNAM, France.
- Doctorat (école d'été): "autonomous Robotics", C. Laugier, 6h, SSIR'12, Ensenada, June 2012, Mexico.
- Ecole d'Ingénieur : "Programmation structurée en C", M. Perrollaz, 36h, L3, Phelma, Grenoble-INP, France.

8.2.2. Supervision

PhD in progress: Chiara Troiani, vision and inertial sensor fusion for 3D navigation, 2011, A. Martinelli.

PhD in progress: Arturo Escobedo, Shared Control navigation, 2011, A. Spalanzani.

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: Boris Grechanichenko, Autonomous Driving, 2013, C. Laugier and D. Vasquez, (cooperation Toyota).

PhD in progress: Roxana Bersan, Decision making for Intelligent Vehicles, 2014, C. Laugier and A. Spalanzani (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.

8.2.3. Juries

- C. Laugier was a reviewer and a member of the defense committee of the PhD thesis of Julien Moras, UTC Compiègne, January 17th 2013.

- C. Laugier was a reviewer and a member of the defense committee of the PhD thesis of Ana Cristina Barata Pires Lopez , University of Coimbra, March 20th 2013.

- C. Laugier and M. Perrollaz were members of the jury of the CNAM Thesis of Nicolas Vignard, CNAM / Inria Grenoble Rhône-Alpes, February 21st 2013.

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