IN PARTNERSHIP WITH:
CNRS

Institut polytechnique de Grenoble

Université Pierre Mendes-France (Grenoble)

Université Joseph Fourier (Grenoble)

Activity Report 2014

Project-Team E-MOTION

Geometry and Probability for Motion and Action

IN COLLABORATION WITH: Laboratoire d'Informatique de Grenoble (LIG)

RESEARCH CENTER
Grenoble - Rhône-Alpes

THEME
Robotics and Smart environments

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Project-Team E-MOTION

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

Creation of the Project-Team: 2004 February 01, end of the Project-Team: 2014 December 31.

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2. Overall Objectives

2.1. Research Program

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 ?

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. New 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

[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 developped 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, 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.

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. Highlights of the Year

- C. Laugier, E. Mazer and K. Mekhnacha have been finalists for the Eurobotics Technology Award 2014. Title "Bayesian perception & Decision: from theory to industrial applications". March 2014.
- A. Nègre, L. Rummelhard, M. Perrollaz and C. Laugier had applied for a petenent "Procédé d'analyise d'une scene dybnamique, module d'analyse et programme d'ordinateur associés".

5.2. A new formulation of the Bayesian Occupancy Filter: a hybrid sampling based framework

Participants: Lukas Rummelhard, Amaury Nègre, Christian Laugier.

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 Hybrid Sampling Bayesian Occupancy Filter (HSBOF) [21] is an evolution of the BOF, in which are introduced additionnal concepts and variables, such as probabilistic classification of the environment between static and dynamic areas, and adaptative motion model structure. The main idea of this new representation is to mix two forms of sampling of the surrounding :

- a uniform sampling, represented as a dense regular grid, for the static objects and the empty areas. In this part, only the occupancy is stored, as the motion model of the static part of the scene is inherent. In practice, the section of the environment includes the vast majority of the scene.
- a non uniform sampling, based on particles drawn in dynamic regions, allowing to focus the computational power on the estimation of their motion. The number of particles used to represent the motion of a particular cell is calculated according to various criterions, such as the confidence in the dynamism of the cell, in its estimated motion, the global needs in the scene, etc. Dynamic regions are resampled at every time step, the amount of particles associated to the different parts of the scene is dynamicly calculated.

The motion field in a cell is then 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, so do 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 static part requires a 2-dimension interpolation to be expressed in the new reference frame, the dynamic part a immediate particle association and a simple rotation of the velocity vectors.

This new version HSBOF is now used in the core of our systems in place of the previous version of the BOF. It presents important improvements in the quality of the estimations, while drastically reducing the memory and computation costs (easily by a 100 factor in term of memory).

5.2.1. Probabilistic grid-based collision risk prediction

Participants: Lukas Rummelhard, Amaury Nègre, Mathias Perrollaz, Christian Laugier.

We developped a new grid-based approach for collision risk prediction [23], based on the Hybrid-Sampling Bayesian Occupancy Filter framework. The idea is to compute an estimation of the Time To Contact (TTC) for each cell of the grid, instead of reasoning on objects. This strategy avoids to solve the difficult problem of multi-objects detection and tracking and provides a probabilistic estimation of the risk associated to each TTC value.

Using motion sensors embedded in the mobile robot (Inertial Measurement Unit, GPS, Wheel speed and steering sensor, visual odometry, etc.), the displacement of the grid between two updates is estimated. The full description of occupancy and dynamics of the scene given by the HSBOF is then used to assess collision risks in the future and even localize them in the grid. The risk evaluation consists in a short-term prediction of the scene configuration (figure 4 and of the robot position. This way a collision likelihood can be computed over time. Using those likelihoods, computed by cell and particle, an estimation of the risk over a period, and a localization of this risk in the grid are performed.

5.3. A new experimental platform for the Technological Research Institute (NanoElec)

Participants: Mathias Perrollaz, Nicolas Turro, Jean-François Cuniberto.

Within the framework of the PERFECT projet (founded by the IRT NanoElec), e-Motion has developped a new experimental platform, based on a Renault Zoe electrical vehicule (Fig. 7). This developpement takes advantage of the experience developped for creating the previous experimental plateform (a Lexus LS600H), and go further by integrating more sensors and more functionalities.

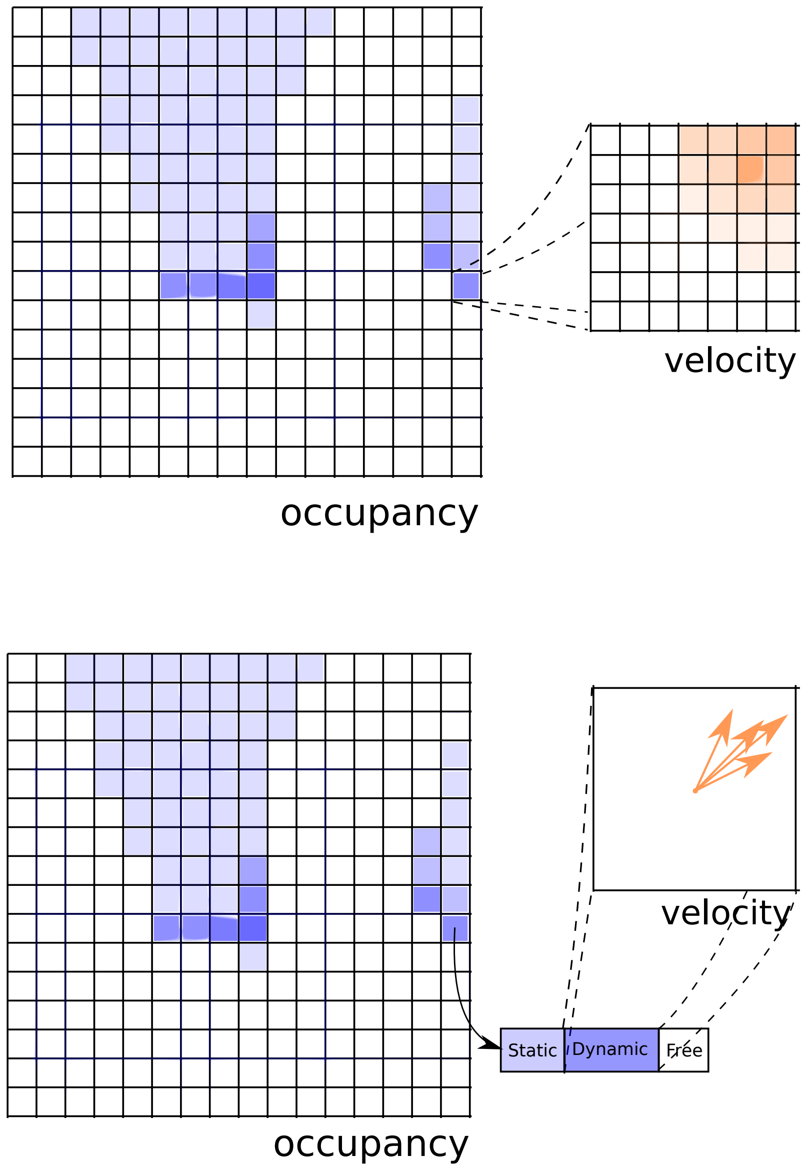


Figure 1.

Data representations in BOF and HSBOF formulation :
(a) Classic BOF representation : a 2 dimension grid, to each cell are assigned an occupancy value and a velocity histogram,
(b) Proposed representation : a 2 dimension grid, to each cell are assigned an occupancy value, a static coefficient $P(V = 0)$ *and a set of particles drawn along* $P(V = v|V \neq 0)$

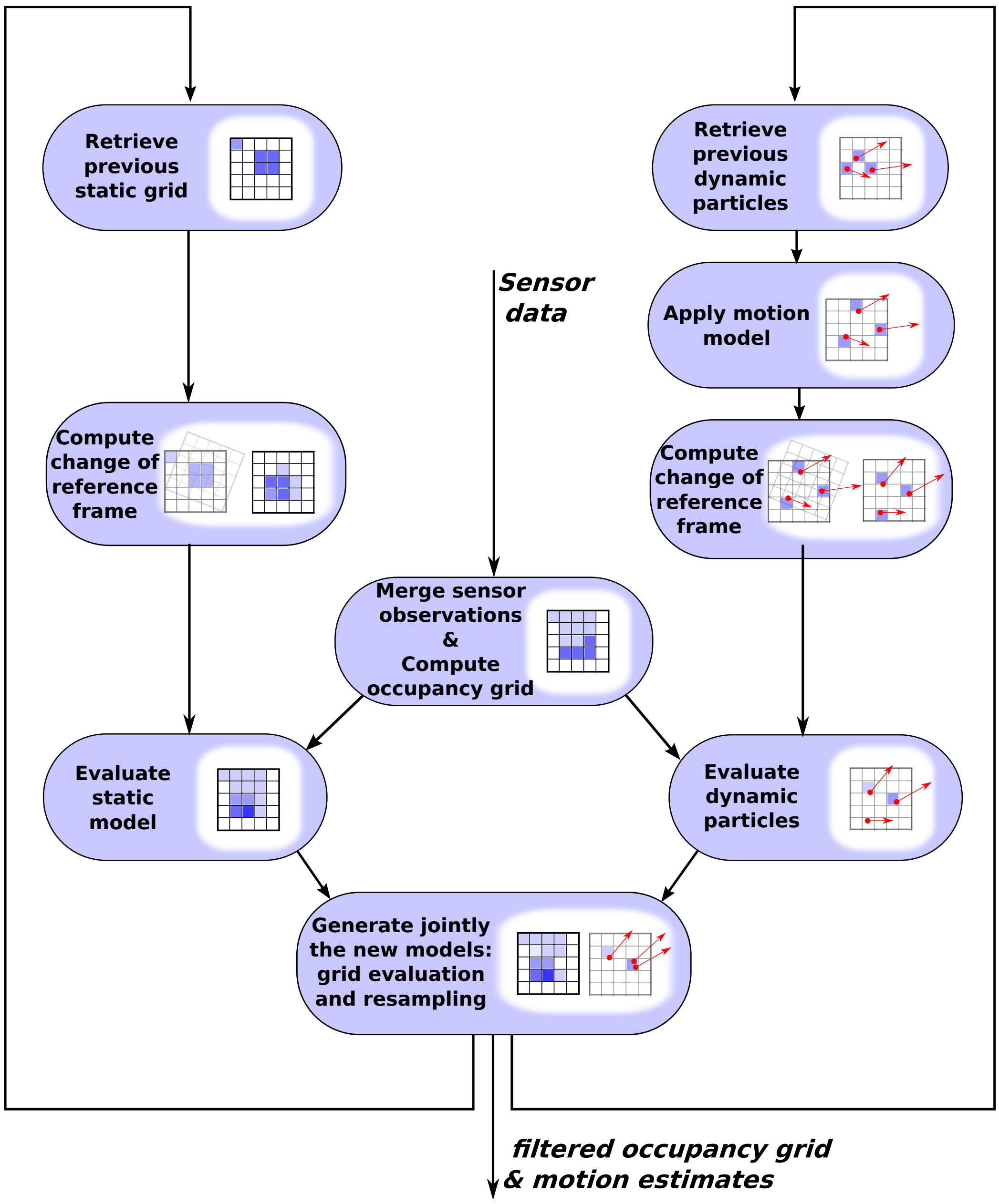


Figure 2. HSBOF algorithm summary. From sensor data instantaneous occupancy grids are successively computed. Those observations are integrated in a Bayesian filter in which coexist and jointly adapt two models, a static grid and a dynamic set of moving particles. The result is obtained by their combination, which provides a filtered occupancy grid as well as inferred motion distributions for cells.

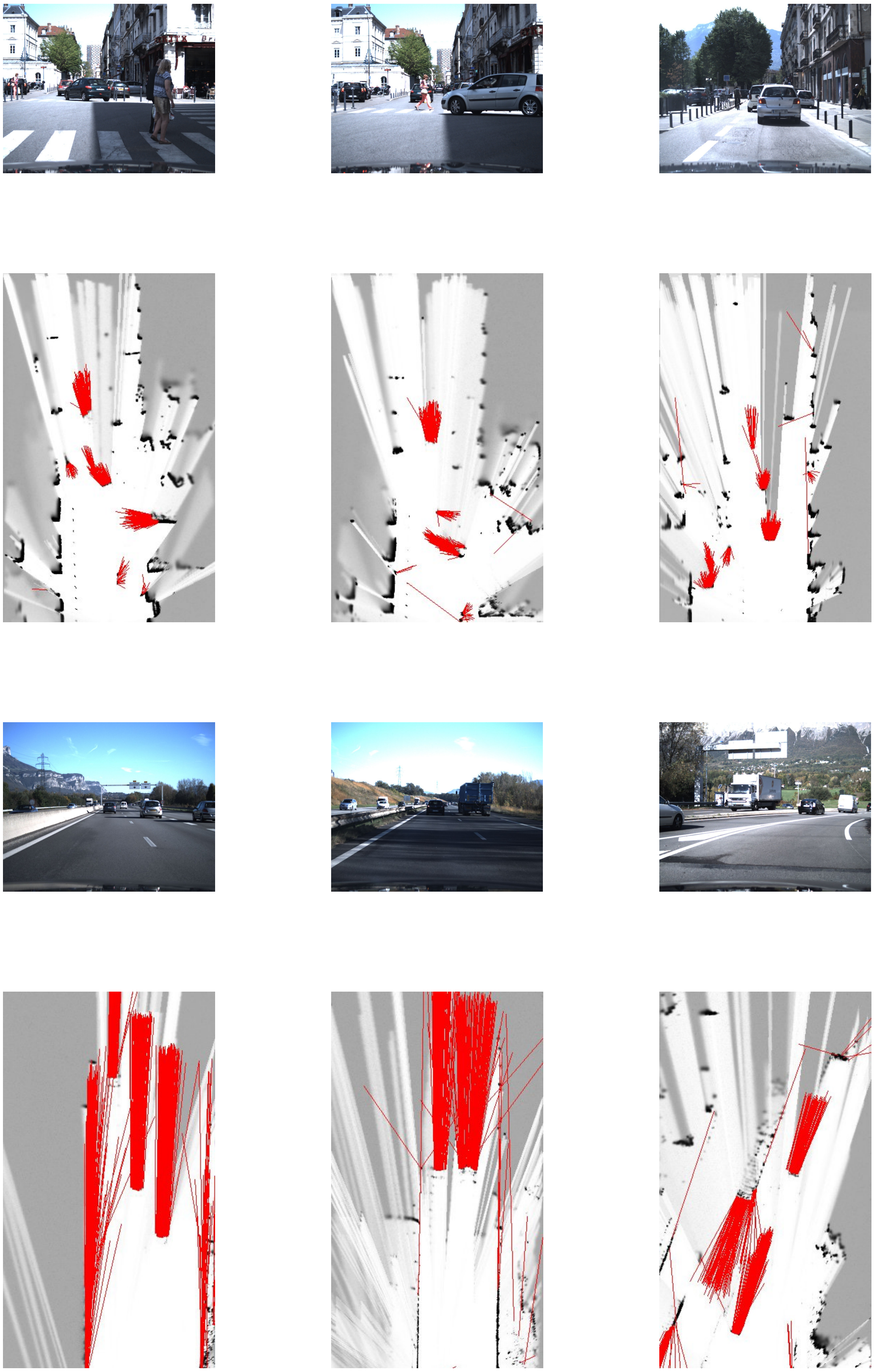


Figure 3. Resulting occupancy grid and velocity field on different urban and highway situations. White cells represent the free space, grey one the unknown space (hidden). Black cells represent the occupied space and red lines represent the average velocity vector for cell with a high dynamic probability.

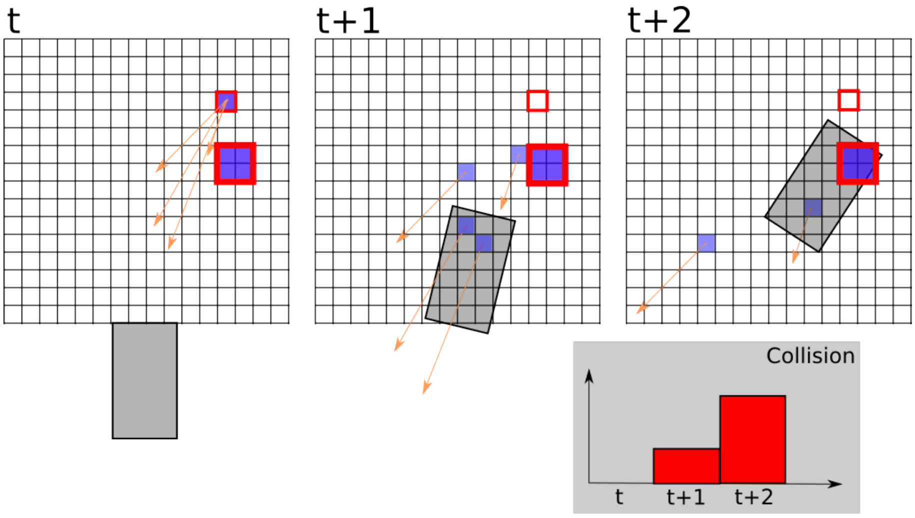


Figure 4. Collision risk estimation over time for a specific cell. The cell position is predicted according to its velocity, along with the mobile robot. This risk profile is computed for every cell, and then used to integrate over time the global collision risk.

(a)

(b)

Figure 5. (a) Fake pedestrian used for experiments. (b) The mannequin is attached to a system with a runner, in order to allow lateral displacements.

(a)

(b)

(c)

(d)

Figure 6. Results of the system. Each image is a visual capture from the embedded camera, the estimated occupancy grid in front of the car (white for occupied, grey for unknown, black for empty), the estimated motion field (if a case is seen as dynamic, a red motion vector showing the average velocity in the cell is drawn on the map) and finally the estimated risk map for 0.5s. The first sequence (a) (b) presents the appearance of an occluded pedestrian, the second (c) (d) a moving pedestrian heading towards the road.

The vehicle is eqquipped with:

- 4 IBEO LUX laser scanners. Each of them scans 4 layers with a field of view of 85 degrees.
- one Velodyne HD64L 3D laser scnanner, capable of scanning 64 layers over 360 degrees.
- one trinocular stereo camera, Point Grey Bumblebee XB3, placed behind the windshield.
- 2 Ueye RGB cameras, looking forward and backward the vehicle.
- one XSens IMU/GPS sensor, used for positionning and ego-motion estimation.
- one ITRI 802.11p on-board unit, allowing V2X communication.

All the synchronization, display, play/record, and developpments capabilities are relying on the ROS middleware. The vehicle is fully operationnal at the end of 2014.
The vehicle is designed for experimenting in both ADAS (Advanced Driver Assistance Systems) and autonomous driving applications. In parallel, V2X communications are installed on the IRT "smart city" environment, so that the vehicle can evolve on this site and interact with it.

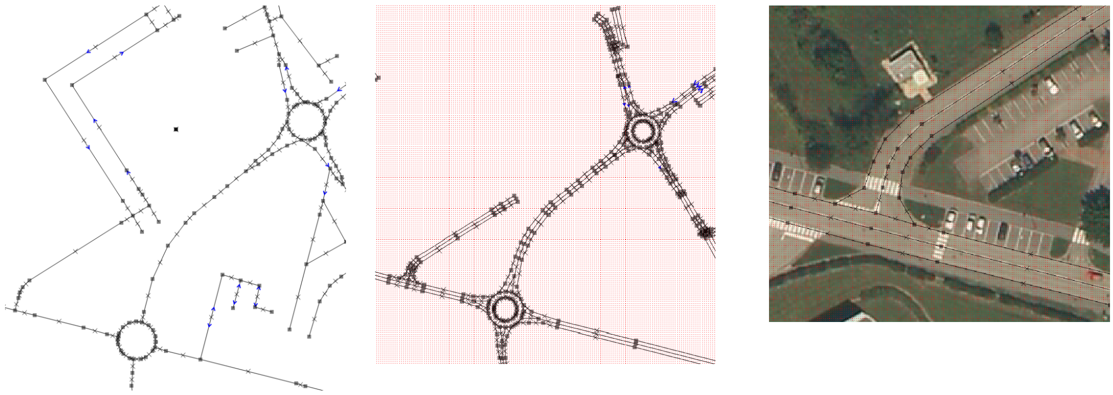
Figure 7. The Zoe experimental platform.

5.4. Visual localization with Open Street Map

Participants: Jean-Alix David, Amaury Nègre.

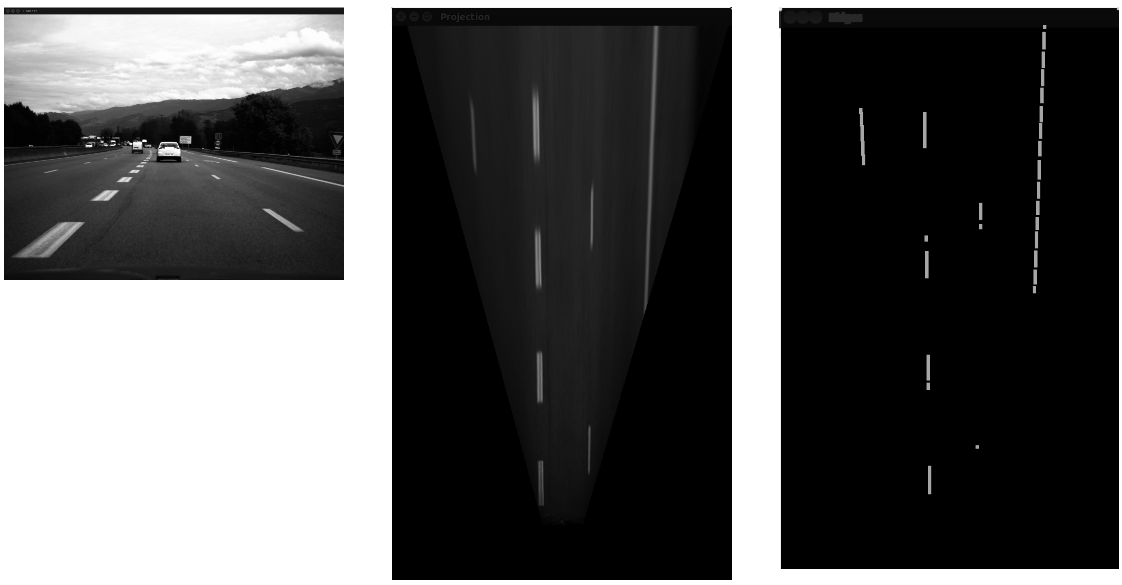
Given the lack of precision of GPS for localization, it is necessary to implement new ways to improve localization. Here we introduce a new method using a geographic map and a camera to do so. The main point of this method is to combine sensor readings and known data about the environment. We detect lines on the road with the camera, and then compare the extracted lines to the ones stored in the map using ICP (Iterative Closest Point) algorithm.

The used map is OpenStreetMap, it allow to have information on the roads and lanes for example, but there is no information about white marking. So we generated semi-autonomously the lines given roads and number of lanes. Moreover we manually corrected the lines for crossroads using satellite image (see Figure 8).



(a) Open Street Map data (b) Generated lines (c) Reprojected lines on aerial image after rectification

Figure 8. Semi-automatic lroad line generation from Open Street Map.



(a) (b) (c)

Figure 9. Line detection in camera images: projection in the ground plane (b) ridge extraction (c).

The line extraction is done using ridge detection on a top-down view of the camera image. Moreover we use GPU acceleration to improve performances during image processing (see Figure 9).

The OSM generated data and the lines extracted from the camera will then be matched and the transformation between the camera and the absolute map will be compute by using an Iterative Closest Point algorithm. In order to improve the precision, a bayesian filtering approach will also be used to merge the previous results with GPS and Inertial Measurement Unit data.

5.5. Human Centered Navigation in the physical world

5.5.1. 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 in 2013 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 [32]. In 2014, Panagiotis left to Lagadic-Sophia and we carried on this work by integrating a planning algorithm to validate the perception part on a real robot. This work was published at IROS 2014 [22].

5.5.2. Goal oriented risk based navigation in social and dynamic environment

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

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 [31]. The likelihood of the obstacles' future trajectory and the probability of occupation are used to compute the risk of collision. A social filter was added to give the robot the ability to move in a social way (see Figure 10). In 2014, we obtained an Inria ADT(ADT PN2) to optimize and share the RiskRRT algorithm. This work is under development. We published in [15] a survey on human-aware navigation.

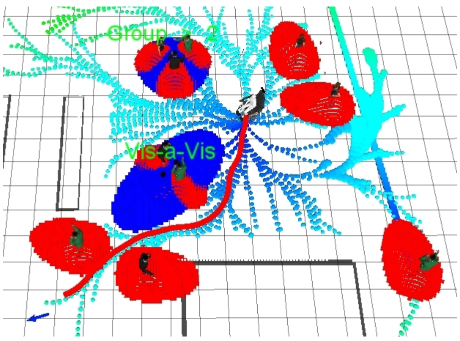


Figure 10. Illustration of the RiskRRT in a social environnment

5.5.3. 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 selects and follows 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. In 2014, we focused on real experiments (see Figure 11 using the wheelchair and results were published in [16], [25], [26].

Figure 11. Switching navigation method between leader following and independent navi- gation. In image 1 the robot is engaged in leader following, while in the remaining it uses RiskRRT for the navigation.

5.5.4. 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 [33]. 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. In 2014, we combined user intention estimation, a navigation using social convention to perform comfortable trajectories (see Figure 12. Results were published in the IROS conference [19]. Arturo Escobedo defended his phD in october 2014.

Figure 12. The Robotic wheelchair assists its user to acheive his task of navigation/.

5.6. Human modeling for situation understanding

5.6.1. Situation understanding and risk assessment for intelligent vehicles

Participants: Dizan Vasquez, Stéphanie Lefèvre, Suryansh Kumar, Yufeng Yu.

The work on this period has been aimed at establishing a solid theoretical and technological base for our research on situation understanding. A step in this direction was the elaboration of an in-depth survey of the current state of the art on the field, prepared together with the university of Berkeley [12]. In the framework of the same collaboration, we have been working on the introduction of human models in current Advanced Driving Assistance Systems (ADAS). This has led to the development of a novel Lane Keeping Assistance System (LKAS) which is able to learn the driver's driving patterns and use them to predict lane departures as well as to generate controls that mimic the driver's style and are, thus, deemed to be more acceptable. The approach has been evaluated against commercial LKAS using real field data, and the results show that the proposed approach is both more efficient and less intrusive than current approaches. This is, for the best of our knowledge the first use of human models withing LKAS and these results illustrate the strong potential that these models may have in ADAS.

Concerning autonomous navigation, we have focused on human-like motion planning for motion prediction. The main hypothesis is that people behave like planners whose motion optimizes some an unknown cost function. Under this assumption, the main challenge becomes to model that cost function and to learn its parameters from demonstrated behavior. This is called, depending on the community, either *Inverse Reinforcement Learning* (IRL) or *Inverse Optimal Control* (IOC). Now, a problem with IRL is that it requires examples of both desirable and undesirable behavior, which are difficult to obtain with a real platform. Additionally, there is no consistent benchmarking methodology to evaluate different approaches. This has motivated our work in a benchmark comprised of: (a) an evaluation methodology; (b) a simulated experimental platform (Fig. 13) based on the Torcs simulator ; and (c) real data gathered with our instrumented Lexus vehicle. The first prototype of this benchmark, developed together with students from Beijing University and IIIT Hyderabad, has been presented this year in a vehicular technologies conference .

5.6.2. Socially compliant robot navigation in human environments

Participants: Dizan Vasquez.

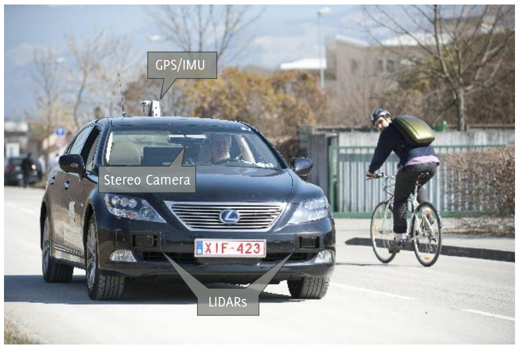


Figure 13. Experimental platforms: left) Our Torcs-based racing simulator; right) sensor-equipped Lexus vehicle.

The models we have applied to intelligent vehicles are also adapted in general to situations where mobile robots share their environment with humans. This has lead us to apply this techniques to the assistive robotics fields, given that it is one of e-motion's major applications axes. Our first effort in this sense has been to design and develop a robust experimental platform with baseline modules for motion planning, perception and social awareness .

In parallel we started working, in collaboration with the University of Freiburg, on a benchmarking platform for social compliant motion planning, close in spirit to the one proposed for intelligent vehicles. The platform (Fig. 14) is described in , it includes several motion planning and feature extraction algorithms as well as a pedestrian simulator based on Helbing's social force model .

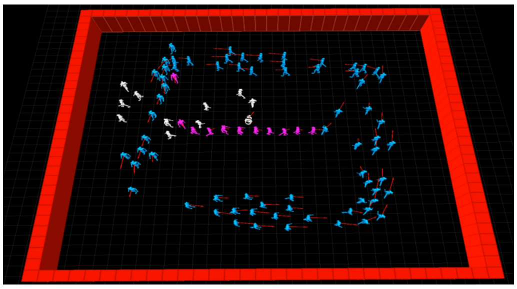


Figure 14. A screenshot of our pedestrian simulator.

5.7. Sensor Fusion for state parameters identification

Participants: Agostino Martinelli, Chiara Troiani.

5.7.1. General theoretical results

During this year we have focused our research on two distinct domains:

- the visual-inertial structure from motion problem;
- the derivation of analytical solutions for the probability distribution of a Brownian motion that satisfies the unicycle constraint.

The research carried out on the first domain is the follow up of our previous activity. We continued to investigate the observability properties of the visual inertial structure from motion and in particular we have analyzed the case when some of the inertial sensors are missing. This analysis has never been provided before and we started this investigation at the end of last year. During this year we confirmed the validity of our preliminary analysis and we also extended them. The preliminary results were obtained by referring to the case when at least five pont features are available and showed 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, if the camera is extrinsically calibrated, the system maintains the same observability properties as in the standard case. These results have been published on the journal Foundations and Trends in Robotics and have also been presented at the last ICRA conference[20].

We recently extended these results by considering the extreme case of a single point feature (i.e., not five). This analysis required to approach an open problem in control theory, called the Unknown Input Observability (UIO). In [20] we proposed a possible method to solve this UIO problem. However, we had to improve this method to deal with this extreme case (i.e., the case of one single point feature). Preliminary results on the extension of this method have been published as a research report [30] and we also plan to present them at the next American Control Conference. By applying this method to our problem, we obtained new interesting results. The new investigation allowed us to conclude that, even in the case of a single point feature, the information provided by a sensor suit composed by a monocular camera and two inertial sensors (along two independent axes and where at least one is an accelerometer) is the same as in the case of a complete inertial measurement unit (i.e., when the inertial sensors consist of three orthogonal accelerometers and three orthogonal gyroscopes). Our first objective is to validate these new results.

Regarding the second domain mentioned above, we have derived a complete analytical solution for the probability distribution of the configuration of a non-holonomic mobile robot that moves in two spatial dimensions by satisfying the unicycle kinematic constraints. The proposed solution differs from previous solutions since it is obtained by deriving the analytical expression of any-order moment of the probability distribution. To the best of our knowledge, an analytical expression for any-order moment that holds even in the case of arbitrary linear and angular speed, has never been derived before. To compute these moments, a direct integration of the Langevin equation has been carried out and each moment was expressed as a multiple integral of the deterministic motion (i.e., the known motion that would result in absence of noise).

For the special case when the ratio between the linear and angular speed is constant, the multiple integrals can be easily solved and expressed as the real or the imaginary part of suitable analytic functions. As an application of the derived analytical results, we also investigated the diffusivity of the considered Brownian motion for constant and for arbitrary time-dependent linear and angular speed. These results have been published on the journal of statistical mechanics [13] and also as a research report [29] where we added more specific considerations about the impact of the derived results on mobile robotics.

5.7.2. Applications with a Micro Aerial Vehicle

We continued our previous activity about the estimation of the relative motion between two consecutive camera views in order to introduce 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.

In particular, during this year, we extended the previous results by removing the assumption of planar motions. In this case, to obtain useful results, we had to include one more point feature (i.e., the proposed algorithms only use two feature correspondences and gyroscopic data from IMU measurements to compute the motion hypothesis). By exploiting this 2-point motion parametrization, we proposed two algorithms to remove wrong data associations in the feature matching process for case of a 6DoF motion. We showed that in the case of a monocular camera mounted on a quadrotor vehicle, motion priors from IMU can be used to discard wrong estimations in the framework of a 2 -point-RANSAC based approach. The proposed methods have been evaluated on both synthetic and real data and presented at the last ICRA conference [27].

5.8. Compiling Probabilistic Programs Onto Reconfigurable Logic Using Stochastic Arithmetic

Participants: Emmanuel Mazer, Marvin Faix.

It is of great interest to perform light weight probabilistic inferences for applications such as sensor fusion. Our goal is to design systems to perform these inferences without using a Von Newman machine nor standard floating point arithmetic. By addressing the core of how computations are made, we can explore the tradeoffs between system precision with power consumption and computation time, enabling artificial systems with limited resources, such as mobile and embedded systems, to better operate under uncertainty. Figure 15 illustrates the tool-chain, which starts from the specification of the Bayesian Program in Bayesian programming language , and evaluates it on a reconfigurable device.

This study is part of BAMBI (Bottom-up Approaches to Machines dedicated to Bayesian Inference, www.bambi-fet.eu) : a European collaborative research project relying on the theory of Bayesian inference to understand the natural cognition and aiming at designing bio-inspired computing devices.

A Bayesian machine has probability distributions as inputs and returns a probability distribution as output. It is defined by a joint probability distribution on a set of discrete and finite variables: $P(M \wedge D \wedge L)$. Where M, D and L are themselves conjunctions of variables, for example $D = D_1 \wedge ... \wedge D_k$. We define the soft evidences on the variables D_k as the probability distribution $\widetilde{P}(D_k)$. These soft evidences will be the inputs of the Bayesian machine.

So, given the soft evidences $\widetilde{P}(D_k)$ and the joint distribution $P(M \wedge D \wedge L)$, the machine will fulfil the specification if it computes:

$$P'(M) = \frac{1}{Z}\sum_{D_1}\widetilde{P}(D_1)...\sum_{D_k}\widetilde{P}(D_k)\sum_{L}P(M \wedge D \wedge L) \tag{1}$$

with

$$Z = \sum_{M}(\sum_{D_1}\widetilde{P}(D_1)...\sum_{D_k}\widetilde{P}(D_k)\sum_{L}P(M \wedge D \wedge L)$$

In other words the machine computes a soft inference based on the joint distribution $P(M \wedge D \wedge L)$.

A modified version of the probabilistic language ProBT is used to specify the machine: the joint distribution, the output and the inputs are specified with this language [2]. The next program is an example of a simple specification using the Python bindings of ProBT.

```
#import the ProBT bindings
from pypl import *
#define the variables
dim3 = plIntegerType(0,2)
D1 = plSymbol(D1,dim3)
D2 = plSymbol(D2,dim3)
M= plSymbol(M,dim3)
#define the distribution on M
PM= plProbTable(M,[0.8,0.1,0.1])
#define a conditional distribution on D1
PD1_k_M = plDistributionTable(D1,M)
PD1_k_M.push(plProbTable(D1,[0.5,0.2,0.3]),0)
PD1_k_M.push(plProbTable(D1,[0.5,0.3,0.2]),1)
PD1_k_M.push(plProbTable(D1,[0.4,0.3,0.3]),2)
```

[2] A free version of ProBT is available at http://www.probayes.com/fr/Bayesian-Programming-Book/ and the version with soft evidence will be placed on www.bambi-fet.eu before the NIPS conference

```
#define a conditional distribution on D2
PD2_k_M = plDistributionTable(D2,M)
PD2_k_M.push(plProbTable(D2,[0.2,0.6,0.2]),0)
PD2_k_M.push(plProbTable(D2,[0.6,0.3,0.1]),1)
PD2_k_M.push(plProbTable(D2,[0.3,0.6,0.1]),2)
#define the joint distribution
model=plJointDistribution(PM*PD1_k_M*PD2_k_M)
#define the soft evidence variables
model.set_soft_evidence_variables(D1^D2)
#define the output
question=model.ask(M)
```

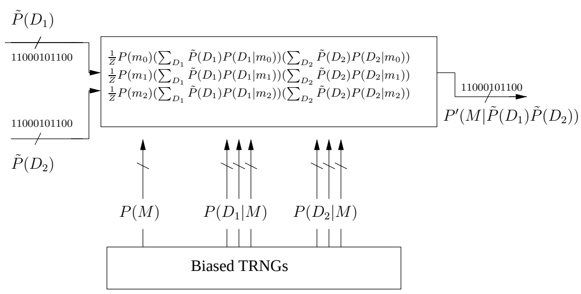


Figure 16. The probabilistic machine corresponding to the given program..

Figure 16 presents the high-level representation of the architecture for the Bayesian Machine. It comprises the main stochastic machine along with the True Random Generators (TRNG), responsible for the generation of the stochastic bit streams for the constants considered in the problem.

The proposed tool-chain is working and accepts any ProBT program with discrete variables as entry. The tool-chain generates a VHDL file which is the description of the stochastic circuit and can be implemented on a FPGA. A Cyclone IV FPGA, from Altera has been targeted as supporting device. A machine has been synthesised to demonstrate the applicability and scalability of the proposed tool-chain. ProBT is also used to compute the exact result using standard arithmetic. This allows to evaluate the results given by FPGA with the synthesised VHDL program.

Figure 17 (right) shows the RTL generated by the synthesis tool, where it is possible to identify the connections between the components, corresponding to the circuit in Figure 17 (left). This circuit was implemented using 6 Logic Elements. The circuit was tested with bit streams integrated over 2^{31} to do the conversion from stochastic to binary.

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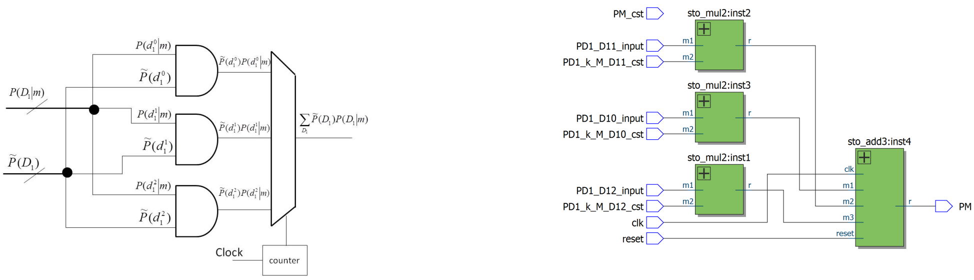

Figure 17. Stochastic circuit computing $\sum_{D1} \widetilde{P}(D_1)P(D_1|m)$ and the corresponding RTL.

We are now focusing on solving the time dilution problem by introducing memory in the architecture. Then we will make an attempt to build a filter with similar ideas by re-fitting the output into the initial joint distribution.

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. 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. Collaborations with Major European Organizations

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.

7.2.1.1. SAMPEN

Title: self adaptive mobile perception and navigation

International Partner (Institution - Laboratory - Researcher):

NTU (TAIWAN)

Duration: 2014 - 2016

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

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

7.3. International Research Visitors

7.3.1. Visits of International Scientists

Mario Garzon, PhD student at Universidade de Madrid was in our team from February 2014 until April 2014.
Yufeng Yu, PhD student at Peking University was in our team until February 2014.
Suryansh Kumar, IIIT-Hyderabad, was in our team from September 2013 to March 2014.

7.3.2. Visits to International Teams

7.3.2.1. Research stays abroad

Chiara Troiani

Date: 2013

Institution: University of Zürich (Switzerland)

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 March 2015.
- 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. March 2014. Editorial: https://hal.inria.fr/hal-00932719.
- A. Spalanzani co-organised a workshop on Assistance and Service robotics in a human environment during IROS 14, Chicago, US, September 2014.
- C. Laugier co-organized (with Ph. Martinet, U. Nunes, and C. Stiller) the 6th Workshop on “Planning, Perception and Navigation for Intelligent Vehicles” at the IEEE/RSJ IROS 2014 conference, Chicago, US, September 2014.
- C. Laugier was an Associate Editor for the IEEE ICRA 2014 conference.
- 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.
- C. Laugier is a member of the Editorial Board of the JSME Robomech Journal.

8.1.1. Keynote talks

- C. Laugier. Keynote talk “Bayesian Perception and Decision: from theory to real world applications”. IEEE/RSJ IROS 2014, Chicago, Sept. 2016.
- C. Laugier. Invited Talk “Nex cars generation". Invited by Tokyo University and Japanese companies. Tokyo, October 2014.
- C. Laugier. Plenary Talk “Key Technologies for addressing the challenge of Autonomous Vehicles”. Int. Conf. on “Innovations for next generation automobule”. Sendai, Japan, October 2014.
- C. Laugier. Invited Talk “Technologies for next cars generation”. IEEE ICARCV 2014, plenary session on the future of robotics, Singapore, December 2014.
- M. Perrollaz and C. Laugier. Invited Talk (given by M. Perrollaz) “Relever les défis des véhicules autonomes”. EMM 2014, 12éme rencontre Européene de Mecatronique. Annecy, June 2014.

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.
- **E-learning**
  - Mooc "Mobile Robots and Autonomous Vehicles" - 6 weeks, C. Laugier, D. Vasquez, A. Martinelli - under finalization, publication spring 2015.

8.2.2. Supervision

PhD defended in 2014: Chiara Troiani, vision and inertial sensor fusion for 3D navigation, 2011, A. Martinelli.

PhD defended in 2014: 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).

Starting PhD: Mathieu Barbier, Decision making for Intelligent Vehicles, 2014, E. Mazer and D. Vasquez (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 Thibault Kruse, University of Munich, January 14th 2015 (Report July 2014).

C. Laugier was a member of the defense committee of the PhD thesis of Chiara Troiani and of Arturo Escobedo.

9. Bibliography

Major publications by the team in recent years

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

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Publications of the year

Articles in International Peer-Reviewed Journals

[10] Q. BAIG, M. PERROLLAZ, C. LAUGIER. *Advances in the Bayesian Occupancy Filter framework using robust motion detection technique for dynamic environment monitoring*, in "IEEE Robotics and Automation Magazine", March 2014, https://hal.inria.fr/hal-00932691

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