INRIA

INSTITUT NATIONAL DE RECHERCHE EN INFORMATIQUE ET EN AUTOMATIQUE

Project-Team e-Motion

Geometry and Probability for Motion and Action

Grenoble - Rhône-Alpes

Theme : Robotics

Activity Report

2010

Table of contents

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Andrea Cristofaro [INRIA fellowship]
Alexandros Makris [INRIA fellowship]
Yong Mao [INRIA + CNRS fellowship]

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Administrative Assistant

Myriam Etienne [Secretary (SAR) Inria]

2. Overall Objectives

2.1. Introduction

Main challenge: The project-team *e-Motion* aims at developing models and algorithms allowing us to build *"artificial systems"* including advanced sensorimotors loops, and exhibiting sufficiently efficient and robust behaviors for being able to operate in *open and dynamic environments* (i.e. in partially known environments, where time and dynamics play a major role), while leading to *various types of interaction with humans*. This Challenge is part of a more general challenge that we call *Robots in Human Environments*. Recent technological progress on embedded computational power, on sensor technologies, and on miniaturised mechatronic systems, make the required technological breakthroughs potentially possible (including from the scalability point of view).

Approach and research themes: In order to try to reach the previous objective, we combine the respective advantages of *computational geometry* and of the *theory of probabilities*. We are also working in cooperation with neurophysiologists on sensorimotor systems, for trying to apply and experiment some *biological models*. This approach leads us to study, under these different points of view, three strongly correlated fundamental research themes:

- *Perception and multimodal modelling of space and motion*. The basic idea consists in continuously building (using preliminary knowledge and current perceptive data) several types of models having complementary functional specialisations (as suggested by neurophysiologists). This leads us to address the following questions : how to model the various aspects of the real world ? how to consistently combine a priori knowledge and flows of perceptive data ? how to predict the motions and behaviors of the sensed object ?
- *Motion planning and autonomous navigation in the physical world*. The main problem is to simultaneously take into account various constraints of the physical world such as non-collision, environment dynamicity, or reaction time, while mastering the related algorithmic complexity. Our approach for solving this problem consists in addressing two main questions : how to construct incrementally efficient and reliable space-time representations for both motion planning and navigation ? how to define an iterative motion planning paradigm taking into account kinematics, dynamics, time constraints, and safety issues ? How to integrate Human-Robot interactions into the decisional processes ?
- *Learning, decision, and probabilistic inference*. The main problem to solve is to be able to correctly reason about prior and learned knowledge, while taking explicitly into account the related uncertainty. Our approach for addressing this problem is to use and develop our bayesian programming paradigm, while collaborating with neurophysiologists on some particular topics such as the modeling of human navigation mechanisms or of biological sensorimotors loops. The main questions we are addressing are the followings : how to model sensorimotor systems and related behaviors ? how to take safe navigation decisions under uncertainty ? What kind of models and computational tools are required for implementing the related bayesian inference paradigms ?

2.2. Highlights of the year

- After a good evaluation of the EPI by INRIA in 2009, and a good evaluation of the EPI by the AERES in 2010, the EPI e-Motion has been renewed for 4 years.
- Renewing the long-term agreement with Toyota (4 years) for common R&D studies in the field of Advanced Driver Assistance Systems. In the scope of this agreement, Toyota has lend an experimental equiped Lexus vehicle.
- C. Laugier has given an invited talk at the transportation week of the universal exposition in Shanghai.

- C. Laugier was program co-chair for the IEEE/RSJ IROS 2010 conference.
- C. Laugier is in charge, since january 2010, of the scientific relations with Asia-Oceania at the INRIA office of International Relations. He is also member of the several commitees at the French Ministry of Research (MESR) and at the French Ministry of Foreign Affairs (MAEE).
- The PhD of Vivien Delsart "Navigation autonome en environnement dynamique: une approche de déformation de trajectoire" has been defended on Oct. 11th 2010.
- The PhD of Luis Martinez "Navigation sûre pour véhicules autonomes en environnement dynamique: une approche par Inevitable collision states" has been defended on november 5th 2010.
- The HDR of Olivier Aycard "Contribution to Perception for Intelligent Vehicles" has been defended on december 2010.

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 (i.e. "Robots in human environments"). In this context, we are focussing onto the following application domains: Future cars and transportation systems, Service and intervention robotics, Potential spin-offs in some other application domains.

3.2. Future cars and transportation systems.

This application domain should quickly change under the effects of both new technologies and current economical and security requirements of our modern society. Various technologies are currently studied and developed by research laboratories and industry. Among these technologies, we are interested in *ADAS*[1] systems aimed at improving comfort and safety of the cars users (e.g. ACC, emergency braking, danger warnings ...), and in *Automatic Driving* functions allowing fully automatic displacements of private or public vehicles in particular driving situations and/or in some equipped areas (e.g. automated car parks or captive fleets in downtown centres).

3.3. Service and intervention robotics.

This application domain should really explode as soon as robust industrial products, easily usable by non-specialists, and of a reasonable cost will appear on the market. One can quote in this field of application, home robots, active surveillance systems (e.g. surveillance mobile robots, civilian or military safety, etc.), entertainment robots, or robotized systems for assisting elderly and/or disabled people. The technologies we are developing should obviously be of a major interest for such types of applications.

3.4. Potential spin-offs in some other application domains.

The software technologies we are developing (for bayesian programming) should also have a potential impact on a large spectrum of application domains, covering fields as varied as the interaction with autonomous agents in a virtual world (e.g.. in the video games), the modelling of some biological sensory-motor systems for helping neurophysiologists to understand living systems, or applications in economic sectors far away from robotics like those of finance or plant maintenance (applications currently covered by our start-up *Probayes* commercializing products based on Bayesian programming).

[1] Advanced Driver Assistance Systems

4. Software

4.1. Advanced Software

- *ProBT.*
  People involved : Juan-Manuel Ahuactzin, Kamel Mekhnacha, Pierre Bessière, Emmanuel Mazer, Manuel Yguel
  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).
- *Cycab Simulator and programming toolbox.*
  People involved : Amaury Nègre, Juan Lahera-Perez, participation of the SED team.
  In order to perform pre-test and to provide help for Cycab developers, a robot simulator has been developed. This simulator is intended to simulate hardware and low-level drivers, in order to produce a temporal behaviour (refresh frequency, scheduling...) similar to what can be found on real robots with real sensors.

  A middleware called Hugr has been developed to allow easy switching between simulated and real platform. Application that uses this middleware do not need to be recompiled when going from the simulator to the real hardware. Moreover Hugr makes it easy to design distributed application. It uses network to share data between applications that are not located on the same machine as easily as if they were on the same one.

  Several sensors and robots have been simulated, among them the most original ones are catadioptric and fisheye cameras. Realistic models have been developed for laser sensors, GPS, cameras, ... All these models rely on state-of-the-art GPU techniques. Computing most of the simulated data on the GPU means that the CPU is free for applications. Therefore there is practically no difference between simulation and real sensors or robots.

  Applications written and tested on the simulated robot can then be settled to the real one without any modification. Sensors and environment are also simulated, so that complete applications can be developed on this test bed.
  The simulator project is available on the INRIA Forge (http://gforge.inria.fr/projects/cycabtk).
- *Bayesian Occupancy Filter (BOF) Toolbox.*
  People involved: Kamel Mekhnacha, Tay Meng Keat Christopher, C. Laugier, M. Yguel, Pierre Bessière, Thierry Fraichard.
  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 á la conduite d'un véhicule et dispositif associé amélioré" n. 0552736 (9 september 2005) and commercialized by ProBayes.

- Fast detection and tracking algorithm (FCTA)
  People involved: Mathias Perrollas, Yong Mao, Igor Paromtchik
  The Fast Clustering and Tracking Algorithm (FCTA) performs detection in 4D occupancy/velocity grids by clustering adjacent cells which have similar occupancy and velocity probability distributions. It also includes a tracking stage, based on a Kalman filter. The association part of the tracking algorithm is speed up using a ROI prediction methodology, allowing real time processing.

4.2. Old Software

Related to close field of research of the e-Motion team-project, these softwares are not used anymore by the researchers of our research team.

- *ColDetect.*
  People involved : Christian Laugier, Kenneth Sundaraj.
  This library has been implemented for providing robust and efficient collision detection, exact distance computation, and contact localisation of three-dimensional polygonal objects. It is patented under the French APP patent #IDDN.FR.001.280011.000.S.P.2004.000.10000. This library is still available on the web and used by several researchers from different countries.
- *Grid Occupancy Wavelets (GROW).*
  People involved : Manuel Yguel, Francis Colas, David Raulo.
  These software components are C++ libraries for designing applications that build dense representation of the occupancy function of a environment from telemetric sensor measurements either 2D or 3D. It is available for Linux. This Grid Occupancy Wavelets software components are declared under the french APP declaration and has been used to scientific experiments.
- *VisteoPhysic.*
  People involved : Cesar Mendoza, Kenneth Sundaraj, Christian Laugier.
  This library provides efficient tools for deformable object simulation. It is patented under the French APP patent #IDDN.FR.001.210025.000.S.P.2004.000.10000.
- *Markov models toolbox.*
  People involved : Olivier Aycard.
  This toolbox is a C++ library for prototyping applications for interpretation of temporal sequences of noisy data. It is available for Linux and PC Windows (Visual C++). The Markov models toolbox has two main components: (i) a definition of Markov models and learning of its parameters component. This component permits to manually define the topology of a Markov model, and to automatically learns the parameters of the defined model. Original learning algorithms have also been developed to automatically build the topology of the model and estimate its parameters. The result of this part is a set of Markov models, where each model is trained (ie, estimated) to recognize a particular type of temporal sequence of noisy data. (ii) an interpretation component. Its goal is to interpret a temporal sequence of noisy data and to determine the most probable corresponding Markov models. This Markov models toolbox is patented under the French APP patent #IDDN.FR.001.280011.000.S.P.2004.000.10000 and has been used to perform a preliminary study of recognition of behaviours of a car driver in cooperation with TOYOTA and also to interpret sequence of noisy sensor data of mobile robots.

5. New Results

5.1. Dynamic World Perception and Evolution Prediction

5.1.1. Distributed Data Fusion and Reasoning Framework for Cooperative Vehicle Applications

Participants: Stéphanie Lefevre, Christian Laugier.

This research is done in collaboration with Renault as part of a CIFRE PhD fellowship that started in June 2009. It was done also in collaboration with Prof. S. Thrun's Driving Group at the Stanford Artificial Intelligence Lab. The recent advances in V2X communication technologies allow the sharing of information among vehicles (V2V) and between vehicles and road infrastructure (V2I). The shared information can be used locally by each entity to extend its awareness horizon and build a better representation of the surrounding environment. Based on this principle Advanced Driver Assistance Systems (ADAS) can be implemented to enhance driving comfort and safety. The focus of this PhD is on cooperative safety applications at intersections (e.g. violation warning, collision warning, intersection assistant).

Intersections are among the most complex environments encountered in road networks. The large number of geometrical configurations, signalization, traffic rules, and vehicle interactions result in many different possible scenarios. Situation assessment is therefore both difficult and fundamental for the safe crossing of intersections. Difficult since the large number of potential scenarios makes it hard to interpret what is happening. Fundamental as any misinterpretation could lead to hazardous situations resulting in accidents. The key issue (and challenge) for situation understanding at intersections is to be able to infer vehicle behavior from incomplete models and uncertain data. In our case the objective is to build a probabilistic model that can estimate the behavior of vehicles at an intersection using:

- information about the ego-vehicle state: position, velocity, force applied on accelerator/braking pedal, turn signal state etc.
- information received via V2X: position, velocity, turn signal state of other vehicles, traffic light state, etc.
- information contained the digital map: geometry of the road network, priority rules, etc.

Therefore for this project on Cooperative Vehicle Applications the first step is to work on situation assessment (e.g. determine if a vehicle is going to stop at an intersection?) and the second one is to do risk assessment (e.g. determine the risk of collision between two vehicles?).

In 2010 we developed a system that estimates a vehicle's intended destination at an intersection based on its current state and on contextual information extracted from the digital map (see illustration in Figure 1). The idea is to use the information on the geometry of the road network and on the connectivity between lanes to build a statistical model of the relationship between the position and turn signal of a vehicle and its intended destination. The model is a Bayesian Network where the values in the conditional probability tables are set using the information extracted from the map. The system is generic to any intersection layout and is capable of handling uncertain input information. So far we conducted experimental evaluation using a set of 42 recorded trajectories of vehicles at two different intersections. The performances were evaluated by measuring how early on average the system made a correct prediction about the destination of a vehicle in five different scenarios including complex situations where the driver's behavior was inconsistent (e.g. the driver put on the left turn signal and turned right). A qualitative evaluation showed that the system handles the different scenarios in a coherent manner even when the driver's behavior is inconsistent. We were also able to demonstrate the advantages of our approach compared with approaches that do not integrate contextual information and do not handle input information uncertainties. This work, in collaboration with the Stanford Artificial Intelligence Lab, resulted in the implementation of the proposed system as a module in the Driving Group's autonomous driving framework. An article describing this work was submitted in November to the IEEE CIVTS'11 symposium [19].

Two conference articles describing the results and findings after the participation of Renault to the European project Safespot ("Cooperative vehicles and road infrastructure for road safety") were published in 2010 [17], [18]. The four Use Cases implemented on the Renault demonstrators were a) Warning - Emergency vehicle approaching an intersection, b) Warning - Emergency vehicle coming from behind, c) Warning - Accident at intersection, d) Warning - Crash predicted at intersection. They are illustrated in Figure 2.

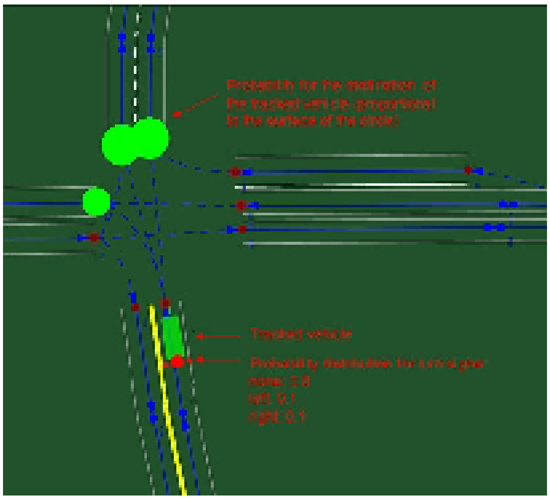


Figure 1. Example result of the probabilistic prediction of a vehicle's destination at an intersection

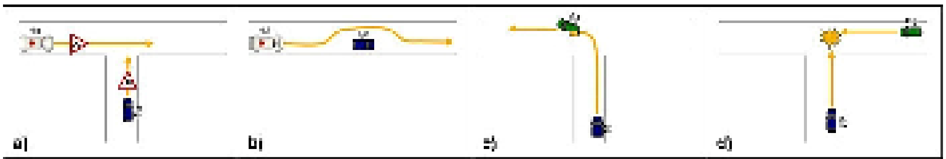


Figure 2. Use Cases implemented on the Renault demonstrators for the Safespot project

5.1.2. ArosdynTestSuite Software

Participants: Yong Mao, Mathias Perrollaz, Igor Paromtchik, Christian Laugier.

An important goal of the ArosDyn project is to develop a system which integrates our recently developped techniques and provides a real-time collision risk estimation in a dynamic environment. To achieve this goal, we designed and implemented the ArosdynTestSuite software. The main features of this software are:

1. The deliberated 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 accelarate 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.

The architecture of this software is shown in Fig.3.

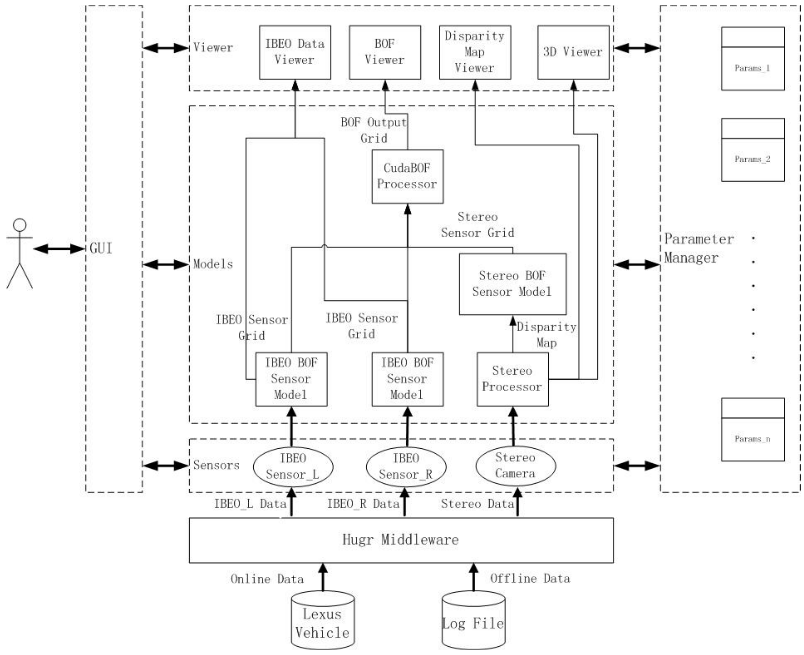


Figure 3. Architecture of ArosdynTestSuite software

In this example, we demonstrate a typical sensor fusion application. We retrieve the raw data from the Hugr middleware and store them in individual sensor objects. Then, by using this framework, we integrate the IBEO Bayesian Occupancy Filter (BOF) sensor model, the stereo sensor processor model, the stereo BOF sensor model and the BOF model together. Finally, different aspects of the computational results are visualized in several viewers. At the same time, all the parameters used by the algorithms can be tuned online.

Several windows of this application are shown in Fig. 4. Here we demonstrate the main window, the 2D viewer of the stereo camera and the lidar, the disparity map of the stereo vision and the compounded BOF grid which is the result of the sensor fusion.

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, as shown in Fig. 5. In this way, the software can work in real-time.

The GPU calculation is based on CUDA library and is carried out in an independent thread. The schematic graph of the GPU computaional thread is shown in Fig. 6.

Furthermore, thanks to the deliberated 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 will be added into this framework.

5.1.3. The ArosDyn Project: Software Development for Robust Analysis of Dynamic Scenes in Dynamic Environments

Participants: Igor Paromtchik, Christian Laugier, Mathias Perrollaz, Mao Yong, Amaury Nègre, John-David Yoder.

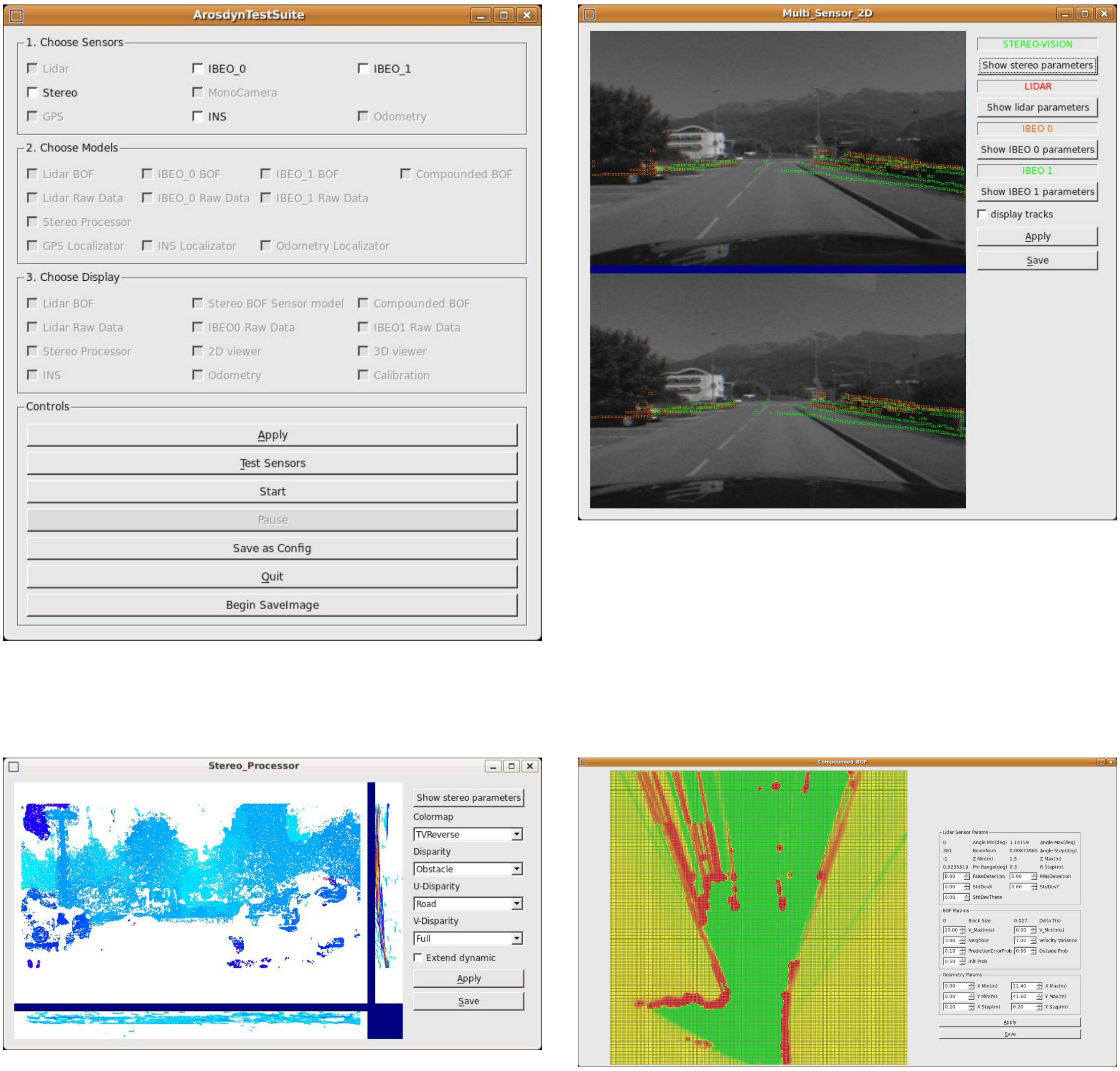


Figure 4. Windows of the ArosdynTestSuite software

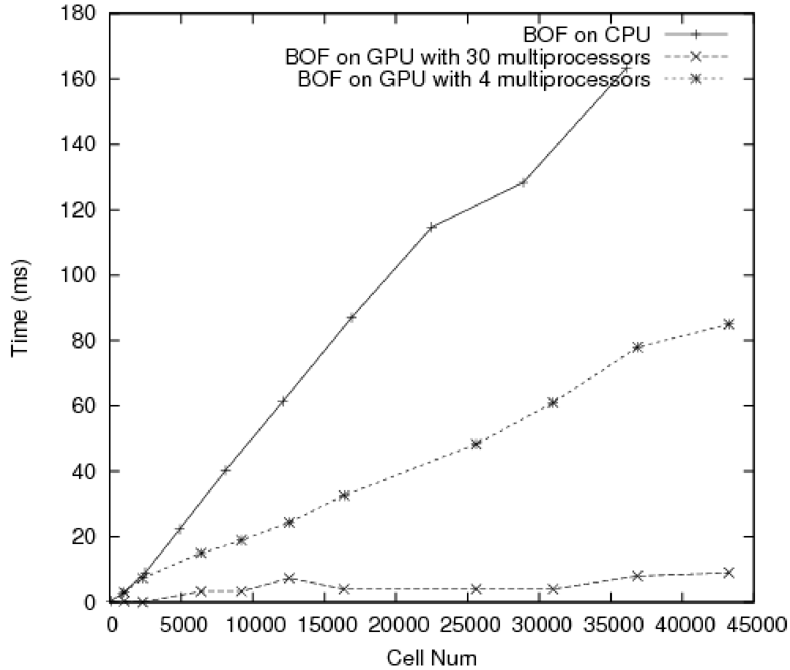


Figure 5. Time performance of BOF on GPU

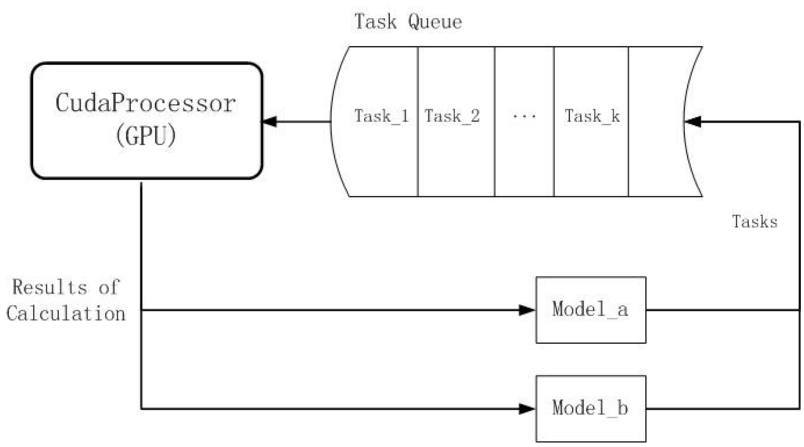


Figure 6. The GPU computational thread

The ArosDyn project (an INRIA Technological Developpement Action) aims to develop embedded software for robust analysis of dynamic scenes in urban traffic environments, in order to estimate and predict collision risks during car driving. The on-board telemetric sensors (lidars) and visual sensors (stereo camera) are used to monitor the environment around the car. The algorithms make use of Bayesian fusion of heterogenous sensor data. The key objective is to process sensor data for detection and tracking of multiple moving objects for estimating and predicting collision risks in real time, in order to help avoid potentially dangerous situations [20], [28]. The local environment is represented by a grid, and the fusion of sensor data is accomplished by means of the Bayesian Occupancy Filter (BOF) [46], [95], that provides to assign probabilities of cell occupancy and cell velocity for each cell in the grid. The collision risks are considered as stochastic variables. Hidden Markov Model (HMM) and Gaussian Process (GP) are used to estimate and predict collision risks and the likely behaviours of multiple dynamic agents in road scenes for a short period ahead.

5.1.4. Object Extraction using Self Organizing Networks and Continuous Background/Foreground Classification

Participants: Thiago Bellardi, Jorge Rios, Alejandro Dizan Vasquez Govea, Christian Laugier.

In many computer vision related applications it is necessary to distinguish between the background of an image and the objects that are contained in it. This is a difficult problem because of the double constraint on the available time and the computational cost of robust object extraction algorithms.

For the specific problem of finding moving objects from static cameras, the traditional segmentation approach is to separate pixels into two classes: background and foreground. This is called *Background Subtraction* [67] and constitutes an active research domain (see [87]). Having the classified pixels, the next processing step consists of merging foreground pixels to form bigger groups corresponding to candidate objects, this process is known as *object extraction*.

In previous work, we focused on the background/foreground classifier exploring the new capability of the extraction algorithm. We implemented a statistical classifier [33] that models the background pixels as Gaussians and we performed the foreground classification based on the Mahalanobis distance between the intensity of the input pixel and its correspondent background model.

In 2009, we adopt the Mixture of Gaussians (MoG) to model the background, We compared the results on combining our clustering algorithm with 4 different background/foreground classification techniques. In 2010 we did more experiments and published in IROS conference [27].

5.1.5. Obstacle detection in occupancy grids, using stereo-vision

Participants: Mathias Perrollaz, Anne Spalanzani, John-David Yoder, Christian Laugier.

Obstacle detection is a widely explored domain of mobile robotics. It presents a particular interest for the intelligent vehicle community, as it is an essential building block for Advanced Driving Assistance Systems (ADAS). In the LOVe project, the E-Motion team proposes to perform obstacle detection within the occupancy grid framework. For this purpose, the Bayesian Occupancy Filter (BOF) was presented as previous work [94]. Its performances and functionalities were demonstrated in particular with data from laser scanner.

To use other sensors in this framework, it is essential to develop an associated probabilistic sensor model that take into consideration the uncertainty over measurements. In 2009, we proposed such a sensor model for stereo-vision[21]. The originality of the approach relies on the decision to work in the disparity space, instead of the classical metric space. This idea gives two major improvements. First, the errors on measurements are more accurately modeled. In particular, the proposed Gaussian model takes into account that the measurement uncertainty is related to the range of observed object. Second, the use of accumulation methods in the disparity space, such as the u-v-disparity approach [71], helps to be computationally efficient.

In the LOVe project, our novel method has been applied to real urban dataset for obstacle detection and tracking. Good detection rates were obtained, even in very dynamic and rich environment such as the downtown driving context. It also appeared from the study of the results that our Gaussian sensor model made it easier to track moving objects using the previously proposed Fast Clustering Tracking Algorithm [81].

In 2010, we improved our sensor model, in order to mimic some features of the sensor models used for range finders. Particularily, we worked on managing visible/occluded areas of the scene. For this purpose, working in the disparity space is still a good way to proceed: the u-disparity plane provides a polar representation in which all the rays of light coming through the camera matrix are parralels. Occlusions and uncertainty are very easy to handle with this representation, thus we propose a probabilistic approach based on this idea [23]. Our approach provides objective advantages over other methods from the state of the art. Moreover, it allows to perform higly parralel computation of the occupancy grid: A.Nègre implemented the approach on GPU using NVIDIA CUDA, reaching very high performances. The complete processing of stereo data can now be done in 6 ms, while more than 150 ms were necessary with the CPU implementation.
In this approach, we only considered the measurements belonging to actual obstacles. Since stereo-vision allows to classify pixels as "road" or "obstacles", the modelization of the scene could be improved by adding the "road" information. We proposed a way to integrate this information in [22].
The sensor model for stereo-vision is used for dynamic scene analysis in the Arosdyn project [20]. In this project, we intend to perform sensor fusion in the occupancy grid framework, using both lidars and stereo-vision. We conducted some early experiments on this approach of sensor fusion, using real data aquired from our experimental vehicle [28].

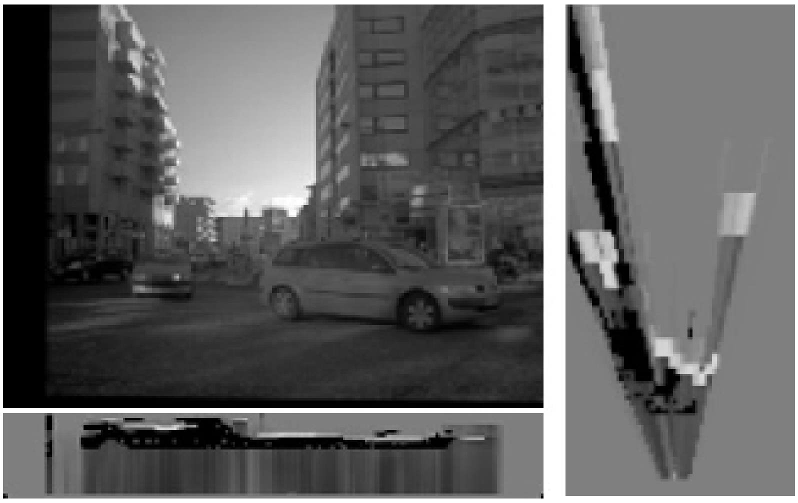


Figure 7. exemple of an occupancy grid computed with our new approach. a) the left image from a stereo pair. b) the occupancy grid computed in the u-disparity plane, and c) the corresponding grid mapped into cartesian space. Light colors correspond to areas with a high probability of occupancy, while dark colors are for low occupancy probability

Figure 7 shows an exemple of occupancy grid computed using our new approach. We can observe that most objects are detected (light color), even if partially occluded (e.g. the sign on the right). Information from the road surface is also taken into consideration (dark areas). Moreover, similar to a laser scanner, it appears that regions in front of objects are seen as partially unoccupied, while less informations is available behind obstacles (occupancy probability is closer to 0.5).

5.1.6. Sensor Fusion

Participant: Agostino Martinelli.

This is a new activity which includes and generalizes some of the results obtained for a specific estimation problem (the problem of sensor calibration). During 2009, the problem of sensor self-calibration in mobile robotics by only using a single feature (e.g. a vertical or a horizontal line) was investigated. The main results achieved during that year were published in [78], [79], [80] and [77].

During 2010 a general framework which applies in any estimation problem has been developed. In particular, the investigation regarded problems where the information provided by the sensor data is not sufficient to carry out the state estimation (i.e. the state is not observable). For these systems the concept of continuous symmetry has been introduced. Detecting the continuous symmetries of a given system has a very practical importance. It allows us to detect an observable state whose components are non linear functions of the original non observable state. This theoretical and very general concept has been applied to deal with two distinct fundamental estimation problems in mobile robotics. The former is in the framework of self-calibration and the latter is in the framework of the fusion of the data provided by inertial sensors and vision sensors. For both problems all the observable modes were analytically derived by analyzing the continuous symmetries. Finally, for both problems several closed-form solution have been analytically derived. Some of the results have been published in [30].

5.1.7. SLAM and Cooperative SLAM

Participants: Agostino Martinelli, Alessandro Renzaglia, Andrea Cristofaro.

This activity has been carried out in the framework of the European project sFly. In particular, we both considered the case of a single vehicle and the case of a team of cooperating vehicles.

Regarding the case of one vehicle, we introduced a new approach to solve SLAM. This approach combines an Information Filter and a non linear optimizer. The basic idea of the suggested technique is to use the Information Filter when the system non linearities are negligible, and to switch to the use of the non linear optimizer when the non linearities are not negligible. Extensive simulations have been performed in order to evaluate the performance of the proposed approach. In particular, a comparison with the Exactly Sparse Delayed-state Filers (ESDF) technique has been carried out. The main results have been published and are available in [14].

Regarding the case of a team of cooperating vehicles, we introduced a new approach to the problem of simultaneously localizing micro aerial vehicles (MAV) equipped with inertial sensors able to monitor their motion and with exteroceptive sensors. The method estimates a delayed state containing the trajectories of all the MAVs. The estimation is based on an Extended Information Filter whose implementation is distributed over the team members. The approach contains two novel contributions. The former is a trick which allows exploiting the information contained in the inertial sensor data in a distributed manner. The latter is the use of a projection filter which allows exploiting the information contained in the geometrical constraints which arise as soon as the MAV orientations are characterized by unitary quaternions. The performance of the proposed strategy has been evaluated with synthetic data. In particular, the benefit of the previous two contributions has been pointed out.

The salient features of our algorithm are as follows:

1. It is robust to single-point failures.
2. It distributes data and computations amongst the robots, hence improving the efficiency of estimation process.
3. It has adjustable processing and communication requirements depending on the resources available to the team.

The main results have been published in [15].

5.1.8. Online Localization and Mapping with Moving Objects Detection & Tracking in Dynamic Outdoor Environments

Participants: Qadeer Baig, Trung-Dung Vu, Olivier Aycard.

Perceiving or understanding the environment surrounding a vehicle is a very important step in driving assistance systems or autonomous vehicles. The task involves both Simultaneous Localization And Mapping (SLAM) and Detection And Tracking of Moving Objects (DATMO). In this context, we have designed and developed a generic architecture to solve SLAM and DATMO in dynamic outdoor environments.

For the SLAM problem, this architecture uses a maximum likelihood approach to build a consistent local map using occupancy grid and to localize the ego vehicle inside the map. After a consistent local map has been constructed, moving objects can be detected using inconsistencies between observed free space and occupied space in the local grid map [97].

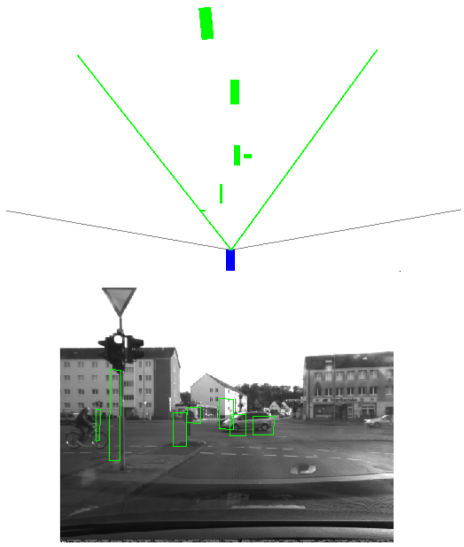


Figure 8. Detection And Tracking of Moving Objects

This year was focused on the integration of vision information and their fusion with laser data to improve the quality of the DATMO process. The Fusion process takes as an input the list of objects provided by both kind of sensors and delivers a fused list of objects where for each object we have information about its pattern and its class. This work has been done in the frame of the european project INTERSAFE2.

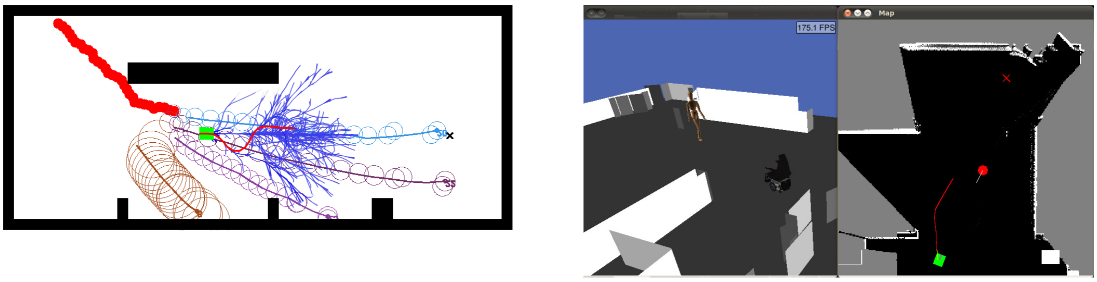
Figure 8 shows the results of the process. In green color, we see the results of the process: all the moving objects present in the field of view of the vision system (green color field of view) are detected by our system.

5.2. Motion planning and Autonomous Navigation in the physical world

5.2.1. Goal oriented navigation in dynamic uncertain environment

Participants: Chiara Fulgenzi, Anne Spalanzani, Christian Laugier.

Navigation in large dynamic spaces has been often adressed 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. We propose a new concept to integrate a probabilist collision risk function linking planning and navigation methods with the perception and the prediction of the dynamic environments. Moving obstacles are supposed to move along typical motion patterns represented by Gaussian Processes. The likelihood of the obstacles' future trajectory and the probability of occupation are used to compute the risk of collision. The proposed planning algorithm is a sampling-based partial planner guided by the risk of collision. The perception and prediction information are updated on-line and reused by the planner. The decision takes into account the most recent estimation. In 2008, we integrated our search algorithm with a representation of typical patterns based on Markov graphs [96] and started to use another representation based on Gaussian Processes [57]. In 2009, we proposed more complete results published in IROS 2009 [55] where a robot need to reach goals in the hall of INRIA avoiding pedestrians. Chiara fulgenzi defended her Ph.D on June 2009 [53]. In 2010 the Risk-RRT Algorithm was integrated in the cycabtk simulator. Results show the performance for a robotic wheelchair in a simulated environment among multiple dynamic obstacles (see fig 9). These results have been submitted to IEEE Transactions on Robotics and also published as a research report [29] On going works focus on adapting the navigation method to the wheelchair taking into consideration that this wheelchair navigates in a populated environment AND transports a person. Next section will details the main points of these research.



(a) (b)

Figure 9. (a) example of trajectory (red thick line) and prediction of pedestrian trajectories (circles), generated paths for the robot (blue lines) and selected one (red path). (b) integration of risk-rrt in the cycabtk simulator

5.2.2. Social conventions based navigation

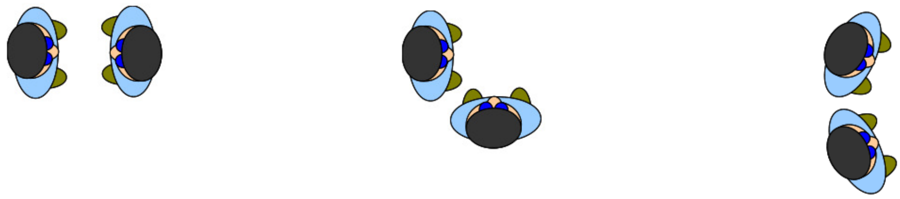
Participants: Jorge Rios-Martinez, Anne Spalanzani, Christian Laugier.

The problem adressed in this work is the autonomous navigation of wheelchairs. If one consider that the navigation system transports a person, the integration of social conventions in the navigation strategy starts to be crucial. In this work, we propose to integrate the notions of personal space and interaction between people. We propose to enrich the knowlegde the robot has, with a representation of the social conventions. The wheelchair must take into consideration interactions to avoid groups of people (even if passing through the group is the “best ”path for a conventionnal planning algorithm), or to join a group with a behavior close to the one of a human. To understand the behaviors of interaction between humans and the management of space we can support us on the works developed in the area of sociology to define some concepts as *Personal space*, *o-space* and *F-formations*.

- Personal Space
  In [59] Hall describes the use of space between humans, he observed the existence of some rules not written that conducted the people to keep distances from others, and others respect this space, he proposed that the space around a person (its *Personal Space*) in social interaction is classified as follows:
  - the public zone > 3.6m,
  - the social zone > 1.2m
  - the personal zone > 0.45m
  - the intimate zone < 0.45m

That definition is important because it could be a useful tool for a robot to understand the intentions of the humans. It is well known that these measures are not stricts and that they change depending on age, culture and type of relationship but the categories proposed explain very well reactions like the uncomfortable sense of a stranger invading your intimate zone or the perception of somebody looking social interaction because he is entering to your social zone.

- F-formation



(a) (b) (c)

Figure 10. Examples of F-formations: (a) Vis-a-vis, (b) L-Shape, (c) C-Shape.

In [65] Kendon observed that people interacting in groups follow some spatial patterns of arrangement. When people are executing some activity they claim an amount of space related to that activity, this space is respected by other people and Kendon referred it as individual's *transactional segment*. This *transactional segment* can vary depending on body size, posture, position and orientation during the activity. Moreover the groups can establish a joint or shared *transactional segment* and only the intervenants have permitted access to it, they protect it and others tend to respect it. The *o-space* is that shared *transactional segment*. A F-formation system is the spatial-orientation arrangement that people create, share and maintain around their *o-space*. We can see in fig. (10) three examples of F-formations.

- Integration to navigation

(a) (b)

Figure 11. Change in the behavior of the autonomous wheelchair. In (a) the navigation don't take in account the personal spaces nor the Vis-a-vis formation, (b) the wheelchair have more information and respect the social conventions of space.

The last concepts have been implemented in a navigation algorithm taking as base the Risk-RRT approach [56], we can see in fig. (11) that the behavior of the wheelchair (in blue) can be changed if we detect the interaction and add a cost to pass inside the area of interaction and a cost to pass in the personal space of pedestrians.

In a dynamic environment is not enough detecting interactions because it could be too late to take a decision, we need to predict that an interaction will take place and when. Our future work will be based in add a model that permits us to predict interactions.

5.2.3. Multi-Robot Distributed Control under Environmental Constraints

Participants: Agostino Martinelli, Alessandro Renzaglia.

This research has been carried out in the framework of the European project sFly. In recent years it is revealed more and more the importance of using multi-robot systems for security application, otherwise impossible to be performed by a single robot. In particular by employing flying robots, many fundamental tasks are now possible. Some of these very important tasks are: surveillance of dangerous regions, like areas of chemical, biological or nuclear contamination; environmental monitoring (*eg* air quality, forest fire); aiding police during surveillance missions and so on. For these purposes we try to develop efficient, robust and versatile methodologies for distributed control of multi-MAV systems under environmental and communication constraints such as global path, obstacles, loss of local communication.

The first problem approached is the optimal coverage of an unknown environment, i.e. finding the optimal deployment for the robots' team to monitor a given region. The solution for the 2-D case without obstacles is already known in literature and it can be obtained analytically. It is based on the Voronoi partition generated by the positions of the robots and the Loyd algorithm [45]. For the non-convex case, i.e. an environment with obstacles, in [92] we firstly proposed a possible strategy based on a combination of the repulsive potential field method and the Voronoi partition. In other words the movement of each robot is generated by the repulsion of the other robots, by the repulsion of the closest obstacle and by the attraction of the center of mass of its Voronoi region. This method allows overcoming the problem of local minima and the robots are better spread in the environment. In this year we have mainly approached the coverage problem by using a new stochastic optimization method. This work is in collaboration with professor Elias Kosmatopoulos and his group, of the Technical University of Crete, partner in the sFly project.

The Kosmatopoulos's group has proposed a new approach for developing efficient and scalable methodologies for a general class of multi-robot passive and active sensing applications [70], [69]. This method employs an estimation scheme that switches among linear elements and, as a result, its computational requirements are about the same as those of a linear estimator. The parameters of the switching estimator are calculated off-line using a convex optimization algorithm which is based on optimization and approximation using Sum-of-Squares (SoS) polynomials. Stable and convergent estimator's performance is guaranteed, overcoming the shortcoming of many existing methodologies where there is always the possibility of estimator error divergence.

The main results obtained for the 2-D case by using this method has been published in [24], [15]. We assume the robots are equipped with global positioning capabilities and visual sensors able to monitor the surrounding environment. The goal is to maximize the area monitored by the team, by identifying the best configuration of the team members. The proposed approach has the following key advantages with respect to previous works:

- it does not require any a priori knowledge on the environment;
- it works in any given environment, without the necessity to make any kind of assumption about its topology;
- it can incorporate any kind of constraints, for instance regarding a possible existing threshold on the maximum distance on the monitored region, or a limited visibility angle;
- it does not require a knowledge about these constraints since they are learnt during the task execution;
- its complexity is low allowing real time implementations.

The previous approach has been then extended for the 3-D case and some simulations using real data, which were collected with the use of a miniature quadrotor helicopter specially designed for the needs of the European project sFLY, have been performed. We developed also a distributed version of this method to solve the same problem. In multi-robot systems, a distributed approach is desirable for several fundamental reasons. The most important are failure of the central station and limited communication capabilities. Furthermore, several simulations show that in our case the distributed algorithm is faster to converge than the centralized one. The results of this work led to the submission of another paper, now under review.

Finally, in [25] we have proposed also a new distributed algorithm for cooperative exploration of an unknown environment. The proposed approach is based on the potential field method. The advantages of using this method are several and well known, but the presence of many local minima does not assure the exploration of the entire environment. Our idea is to preserve these advantages but overcome the problem of local minima by introducing a leader in the team which has a different control law, unaffected by this problem. Furthermore, we consider also the case of several local leaders, dynamically selected on the basis of a hierarchy within the team.

5.2.4. Trajectory Deformation

Participants: Vivien Delsart, Thierry Fraichard.

Where to move next? is a key question for an autonomous robotic system. This fundamental issue has been largely addressed in the past forty years. Many motion determination strategies have been proposed. They can broadly be classified into *deliberative* versus *reactive* strategies: deliberative strategies aim at computing a complete motion all the way to the goal, whereas reactive strategies determine the motion to execute during the next time-step only. Deliberative strategies have to solve a motion planning problem [74]. They require a model of the environment as complete as possible and their intrinsic complexity is such that it may preclude their application in dynamic environments. Reactive strategies on the other hand can operate on-line using local sensor information: they can be used in any kind of environment whether unknown, changing or dynamic, but convergence towards the goal is difficult to guarantee.

To bridge the gap between deliberative and reactive approaches, a complementary approach has been proposed based upon *motion deformation*. The principle is simple: a complete motion to the goal is computed first using a priori information. It is then passed on to the robotic system for execution. During the course of the execution, the still-to-be-executed part of the motion is continuously deformed in response to sensor information acquired on-line, thus accounting for the incompleteness and inaccuracies of the a priori world model. Deformation usually results from the application of constraints both external (imposed by the obstacles) and internal (to maintain motion feasibility and connectivity). Provided that the motion connectivity can be maintained, convergence towards the goal is achieved.

The different motion deformation techniques that have been proposed [90], [66], [39], [72], [98] all performs *path deformation*. In other words, what is deformed is a geometric curve, *ie* the sequence of positions that the robotic system is to take in order to reach its goal. The problem with path deformation techniques is that, by design, they cannot take into account the time dimension of a dynamic environment. However in many cases, it would be more appropriate to try to anticipate the motion of dynamic obstacles by considering their current and future motion, in the aim to avoid collision with them in a close future. To achieve this, it is necessary to depart from the path deformation paradigm and resort to **trajectory deformation** instead. A trajectory is essentially a geometric path parametrized by time. It tells us where the robotic system should be but also when and with what velocity. By taking into account a forecast model of the future behavior of obstacles, both *spatial and temporal* deformations may take place. They result from the application of *external forces ie* repulsive forces exerted from the obstacles and *internal forces* used to maintain the connectivity of the trajectory. Both path and velocity profiles of the robotic system may thus be altered to adapt the behavior of the robot to its environment.

Our trajectory deformer named `Teddy` is designed to be one component of an otherwise complete autonomous navigation architecture. A motion planning module is required to provide `Teddy` with the nominal trajectory to be deformed. `Teddy` operates periodically with a given time period. At each cycle, `Teddy` outputs a deformed trajectory which is passed to a motion control module that determines the actual commands for the actuators of the robotic system. The work on `Teddy` culminated in 2010 with the completion of Vivien Delsart's PhD.

5.2.5. *Trajectory Generation*

Participants: Vivien Delsart, Thierry Fraichard, Luis Martinez-Gomez.

This research topic is related to our work on Trajectory Deformation (see Section 5.2.4). The main difficulty of trajectory deformation lies in the maintenance of the connectivity of the trajectory for complex dynamic systems since it requires the characterization of their set of reachable states. To solve this problem, we have decided instead to base the internal forces computation upon a *steering method* computed by a new **trajectory generator** called `Tiji`.

Trajectory generation for a given robotic system is the problem of determining a feasible trajectory (that respects the system's dynamics) between an initial and a final state. From the preliminary work of Dubins [49] to the latest methods used by the Carnegie Mellon University during the *Darpa Urban Challenge* [61], many trajectory generation methods have been proposed like *primitive combinations* [49], [91], [63], [52], *two-point boundary value problems* [68], [62], [73], or *variational approaches* [47], [58], [64], [61].

Among all these approaches, it is interesting to note that, in no circumstances, have people tried to compute a trajectory reaching the goal state at a specific *time instant*. However, several problems like Trajectory Deformation require to fix the final time or at least an interval of time during which a goal state must be reached. We proposed thus a trajectory generation scheme called `Tiji` which integrates the final time constraint. `Tiji` is geared towards complex dynamic systems subject to differential constraints, such as car-like vehicles, and its efficiency warrants it can be used in real-time. The approach is similar in spirit to that of [61]: a parametric trajectory representation is assumed in order to reduce the search space. An initial set of parameters is selected yielding a trajectory that does not necessarily reach the goal state. The parameter space is then searched and efficient numerical optimization is used to optimize a cost function involving the distance between the end of the trajectory computed and the (goal state, final time) pair. Should the goal state be unreachable (if the final range of time is ill-chosen), the method returns a trajectory that ends as close as possible to the (goal state, final time) pair. `Tiji` differs from previous works first because it takes into account the final time constraint and also because the control definition chosen is such that it ensures that all trajectory constraints are met. The latest results concerning have been reported in [16]. They are also included in Vivien Delsart's PhD.

5.2.6. *Inevitable Collision States*

Participants: Antoine Bautin, Thierry Fraichard, Luis Martinez-Gomez.

Safe navigation is undoubtedly a critical issue that needs to be solved for autonomous mobile robots/vehicles to leave labs environments and be deployed in real world applications. This problem has been studied extensively by the robotics community and some results were illustrated rather brilliantly by the 2007 DARPA Urban Challenge[2]. The challenge called for autonomous car-like vehicles to drive 96 kilometers through an urban environment amidst other vehicles. Six autonomous vehicles finished the race thus proving that autonomous urban driving could become a reality. Note however that, despite their strengths, the Urban Challenge vehicles have not yet met the challenge of fully autonomous urban driving (how about handling traffic lights or pedestrians for instance?). Moreover, at least one collision took place between two competitors. It shows that *motion safety* (the ability for an autonomous robotic system to avoid collision with the objects of its environment) remains an open problem in mobile robotics.

To address this issue, we have explored the novel concept of *Inevitable Collision States* (ICS) since 2002. An ICS for a given robotic system is a state for which, no matter what the future trajectory followed by the system is, a collision with an object eventually occurs. For obvious safety reasons, a robotic system should never ever end up in an ICS. ICS have already been used in a number of applications: (i) mobile robot subject to sensing constraints, *ie* a limited field of view, and moving in a partially known static environment [51], (ii) car-like vehicle moving in a roadway-like environment [86] [34], (iii) spaceship moving in an asteroid field [41]. In

[2] `http://www.darpa.mil/grandchallenge`.

all cases, the future motion of the robotic system at hand is computed so as to keep the system away from ICS. To that end, an ICS-Checker is used. As the name suggests, it is an algorithm that determines whether a given state is an ICS or not. Similar to a Collision-Checker that plays a key role in path planning and navigation in static environments, it could be argued that an ICS-Checker is a fundamental tool for motion planning and navigation in dynamic environments. Like its static counterpart, an ICS-Checker must be computationally efficient so that it can meet the real-time constraint imposed by dynamic environments.

This work has yielded first a *generic* and *efficient* ICS-Checker for planar robotic systems with arbitrary dynamics moving in dynamic environments, and second, an ICS-based collision avoidance scheme, *ie* a decision-making module whose primary task is to keep the robotic system at hand safe from collisions. This collision avoidance scheme, *guarantees motion safety with respect to the model of the future which is used*. They have been documented in 2010 in Luis Martinez-Gomez's PhD.

Finally we have addressed how the ICS concept can be extended to handle the uncertainty inherent to the future. So far the characterization of the ICS has been based upon deterministic models of the future. In other words, each moving object was assumed to follow a given nominal trajectory (known a priori or predicted). Such deterministic models provide a clear-cut answer to the motion safety issue: a given state is an ICS or not (simple binary answer). However, such models are not well suited to capture the uncertainty that prevails in real world situations, in particular the uncertainty concerning the future behaviour of the moving objects. Our contribution is a probabilistic formulation of the ICS concept. Probabilistic ICS permit the characterization of the motion safety likelihood of a given state, likelihood that can later be used to design safe navigation strategies in real world situations. This is the first step towards the applicability of the ICS framework to real robots operating in uncertain dynamics environments. The first results concerning Probabilistic ICS have been reported in [13].

5.2.7. Anthropomorphic Navigation

Participants: Thierry Fraichard, Leonardo Scandolo.

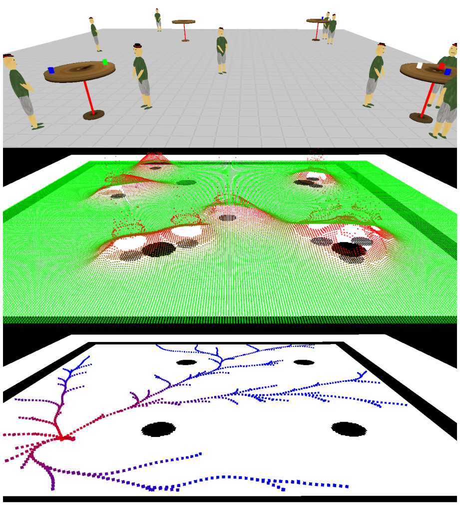


Figure 12. A human-populated environment (top); the corresponding social costmap (middle); a trajectory planning tree (bottom).

Nowadays, robotic systems are increasingly moving among and interacting with human beings. The presence of people has an impact on the way robots should move: you do not move around a person the way you would around a piece of furniture. In general, when one interacts with a human being (to avoid him, to salute him, to pass him an object, etc.), one obeys a number of unspoken social rules, *eg* maintaining an appropriate distance. These rules must be identified and integrated in the navigation scheme of robotic systems so that their behaviour resemble that of a person thus facilitating the integration of robots in human-populated environments and their acceptance.

The primary contribution of this novel line of research is a navigation scheme that is *anthropomorphic*, *ie* that emulates human behaviors and seeks to adhere to these social rules. Unlike previous works in this area, the focus herein is on dynamic scenarios. The navigation scheme proposed explicitly reasons on the future behavior of the people involved so as to produce better socially acceptable trajectories (not to mention safer trajectories as well). The navigation scheme relies upon a novel cost function called the *social costmap* that captures in a unified way the different social rules imposed by the people populating the robot's workspace (see Fig. 12). The first results concerning anthropomorphic navigation will be presented during the 2011 IEEE Int. Conf. on Robotics and Automation.

5.3. Bayesian Modelling of Sensorimotor Systems and Behaviors

5.3.1. Models and Tools for Bayesian Inference

Participants: Juan-Manuel Ahuactzin, Pierre Bessière, Emmanuel Mazer, Manuel Yguel.

This work has been done in collaboration with our Start-up Probayes. ProBT is a C++ library for developing efficient Bayesian software [82] [36]. This library has two main components: (i) a friendly Application Program Interface (API) for building Bayesian models and (ii) a high-performance Bayesian inference and learning engine allowing execution of the probability calculus in exact or approximate ways.

The aim of ProBT is to provide a programming tool that facilitates the creation of Bayesian models and their reusability (http://www.probayes.com/). Its main idea is to use "probability expressions" as basic bricks to build more complex probabilistic models. The numerical evaluation of these expressions is accomplished just-in-time: computation is done when numerical representations of the corresponding target distributions are required. This property allows designing advanced features such as submodel reuse and distributed inference. Therefore, constructing symbolic representations of expressions is a central issue in ProBT.

Since a few years the main development of ProBT has been carried out by Probayes: a spin-off born from the e-motion project. Both, e-motion and Probayes, are part of the European project Bayesian Approach to Cognitive Systems (BACS). The development of ProBT has been done taking into account the goals of the BACS project partners.

5.3.2. Bayesian programming applied to a multiplayer video games

Participants: Gabriel Synnaeve, Pierre Bessière.

The problem addressed in this work is the autonomous replacement of a human player. We worked on two types of games, and so two types of players. From a research point of view, multiplayer games are interesting because they stand for a good in-between of the real world and simulations. The world is finited and simulated (no sensors problems) but we didn't wrote the simulation and the other players are humans (or advanced robots in the case of AI competitions).

The first work was on the control of a virtual avatar by an artificial intelligence in a massively multiplayer online role playing game (MMORPG). The outcome for the video games industry is to give the possibility to the developers to train mobs (non-playing characters) instead of programming them. This, of course, should drastically reduce development time and hopefully leads to more intelligent and more human like mobs. A MMORPG contains several different situations, we tackled the problem of choosing what to do (which spell/skill to use) and on which target in a setup where both allies and foes are present. We developed the model in Bayesian programming. This work resulted in a publication at MaxEnt 2010 [26].

The second work was on artificial intelligence for real time strategy (RTS) games. RTS games consist in controlling workers and armies to develop economy, technology, armies, and beat your opponent. Il involves strategy, tactics, and human skill (unit management). In 2010, we particularly worked on unit management with a Bayesian robotic programming model for unit control. Each unit is considered as a modal (scout, flock, fight, etc.) robot with sensory informations such as the topographical information (cliffs, buildings), its allies and foes positions and speeds (see figure 13). The units group works as a hierarchical multi-agents system without inter-unit communication. We applied this work to Starcraft: Broodwar in the context of the AIIDE 2010 Starcraft AI Competition and it gave promising results.

Figure 13. Possible direction to choose from to move the unit. Green units are allies, purple ones are foes.

5.3.3. Biochemical Bayesian Computation

Participant: Pierre Bessière.

Biochemical Probabilistic Inference is a new area of research which started in 2008 in close collaboration with LPPA-College de France and ProBAYES. In september 2010 Pierre Bessière moved to LPPA to boost this part of the work but stayed an associated researcher of E-motion.

Living organisms need to quickly react without waiting for a perfect evaluation of the consequences of their action. For instance, we perceive objects from retinal stimulation without the need for a complete knowledge of the underlying light-matter interactions. To account for this ability to reason with incomplete knowledge, it has been recently proposed that the brain works as a probabilistic machine, evaluating probability distribution over cognitively relevant variables. A number of Bayesian models have been shown to efficiently account for perceptive and behavioural tasks (see [11] for a survey). However, little is known about the way subjective probabilities are represented and processed in the brain.

Numerous biochemical cellular signalling pathways have now been unravelled. These mechanisms involve the strong coupling of macromolecular assemblies, membrane voltage and diffusible messengers, including intracellular Ca2+ and other chemical substrates like cyclic nucleotides. Since transition between allosteric states and messenger diffusion are mainly powered by thermal agitation, descriptive models at the molecular level are also based on probabilistic relationships between biophysical and biochemical state variables [60][12].

Our proposal is based on the existence of a deep structural similarity between the probabilistic computation required at the macroscopic level to account for cognitive, perceptive and sensory motor abilities and the biochemical interactions of macromolecular assemblies and messengers involved in cellular signalling mechanisms. Our working hypothesis is then that biochemical processes constitute the nanoscale components of cognitive Bayesian inferences.

We propose 3 main novel ideas:

- A new model of computation founded on Bayesian algebra instead of the universally used Boolean algebra.
- A new viewpoint on the biochemistry of cell signalling considered as the possible in vivo implementation of probabilistic computation.
- New perspectives on conceptions of manmade inference and decision devices as the new model of computation changes completely the requirements for such devices.

To be more specific, the starting ideas are the following:

- The mathematical atoms for probabilistic computation are not Boolean values but ratio of probabilities with a range between 0 and $+\infty$ (Bayesian values).
- Consequently, the fundamental set of computational rules is not Boolean algebra but a probabilistic algebra (Bayesian algebra) on these positive values.
- Analogous to logic gates for Boolean algebra, it is possible to design Bayesian gates that perform these basic probabilistic operations. The transfer functions of these Bayesian gates are rational function of the entries.
- Boolean gates can be assembled into complex architectures to produce a logical computer. In a similar way, Bayesian gates could be assembled in a modular architecture to produce a probabilistic computer.
- Concentration of macromolecules or messengers, membrane potential and spike frequencies are positive quantities, which are candidates to encode Bayesian values.
- Some biochemical dynamics and equilibriums between populations of allosteric macromolecules and messengers can be seen as biochemical implementation of Bayesian gates.
- Signal transduction in cells and between cells offers a wide range of possible implementations for probabilistic reasoning.
- The interplay between local biochemical mechanisms and distant electrical propagation in neurons is the key level to understand brain computation.

The addressed scientific challenges imply a paradigm shift to a post Boolean computational approach that should have long term impact on different fundamental questions in both cognitive and ICT sciences:

- From a theoretical and mathematical point of view, changing the range of the atomic manipulated quantities from binary values to positive values and changing the fundamental mathematical structure from Boolean algebra to Bayesian algebra, means that some fundamental questions have to be reconsidered. For instance: what is a formal system based on probabilistic rules of inference? What are a theorem and a proof in such a formal system? What is meant by consistence and completeness for such probabilistic formal systems? What is a formal grammar in such a perspective and consequently what kind of computing language can we build and use? What kind of architectures may result from these grammars? And, finally, what kind of parsers or compilers should we build to program or synthesize probabilistic machines?
- From a life science point of view, considering that cells, neurons and brain are manipulating probabilities of variables instead of their values may also change the nature of the models. Some open questions are, for instance: how is information encoded at the different scales (molecular, intra-cellular, cellular, inter-cellular, population, system)? How is information processed at these different scales? How is information memorized at these different scales? What is meant by learning and adaptation at these different scales? Do sensory-motor systems perceive values or probabilities of values? How do they make decisions on the actions to perform?

- Finally, from an ICT point of view the same questions as for life science have to be answered. However, for each of them rather than understanding how nature is solving these questions the problem is to imagine engineering efficient solutions. Digital electronics has been conceived and optimized to treat Boolean values, consequently a fundamental question is: is it still the better physical substrate to treat probabilistic values?

6. Contracts and Grants with Industry

6.1. 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 danger. 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.

6.2. ADT ArosDyn

[Nov 2008 - Oct 2011]

The Technology Development Action (ADT) ArosDyn aims at the development of embedded software for robust analysis of dynamic scenes and assessment of risk during car driving. The system will be used in the scope of a Driver Assistance System. ADT ArosDyn is supported by the INRIA's Direction of Technological Development (DDT).

The principal participants of ArosDyn are the project-teams: e-Motion, PERCEPTION, and SED of INRIA Grenoble Rhône-Alpes, and a project-team EVOLUTION of INRIA Sophia-Antipolis. The spin-off company Probayes and a project-team PRIMA of INRIA Grenoble Rhône-Alpes help develop the specialized modules of ArosDyn.

The robustness of the analysis methods is based on the Bayesian fusion of sensor data. The applied algorithms provide to detect and track in real time multiple moving objects in various traffic scenarios. The perception of traffic environment relies on the processing of range and visual information gathered by a laser scanner and a stereo vision camera. These two types of sensors possess complementary technical features. They ensure the detection of objects in various traffic scenarios. The proprioceptive perception makes use of the inertial and odometry sensors.

6.3. Renault

[Jan 2010 - Feb 2013]

This contract is linked to the PhD Thesis of Stephanie Lefevre. 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 will be considered in the scope of this study.

6.4. GRAAL

[January 2009 - December 2011]

The Graal project aims to produce a generic behaviour construction toolkit for video games and small autonomous robots. It is based on probabilist modelling techniques, and will last two years, starting in January 2009. It involves four partners :

- INRIA/e-Motion provides the core scientific basis for probabilist modelling and autonomous robot programming;
- Probayes ("Born of INRIA" in 2003) builds upon its generic Bayesian inference engine ProBT, and its expertise of decision systems;
- POB-Technology develops small robots for education and entertainment, sold in high schools and universities all over the world;
- Ageod (in the project during its first year) developed simulation-like historic strategy games.

The goal of the project is the extension and application of Bayesian modelling techniques for industrial behaviour construction :

- programming and maintaining complex behaviours for virtual entities; - teaching simple behaviours to small robots;
- bringing behaviour modification into the hands of students and hobbyists;
- integrating probabilistic reasoning into the tools of industrial behaviour programmers.

The Graal project is funded as a FUI (Fonds Unitaire Interministériel) project by the French Ministère de l'Industrie, the Rhône-Alpes region, and the Greater Lyon metropolitan area. It is labelled and supported by the Imaginove (game and entertainment) and Minalogic (intelligent miniaturized products) clusters.

6.5. 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.

7. Other Grants and Activities

7.1. European projects

7.1.1. INTERACTIVE

[January 2010 - January 2014]

Interactive is the most important european project of FP7 dedicated to Advanced Driver Assistance System (ADAS) (more than 30 partners and 20 Meuros of funding). One of the main goal of this project is to design and develop generic architecture for perception solutions for ADAS. e-motion will play a key role in this task following-up its cooperation with Daimler.

7.1.2. BACS (Bayesian Approach to Cognitive Systems)

FP6-IST-027140 [January 2006 - February 2011]

Despite very extensive research efforts contemporary robots and other cognitive artifacts are not yet ready to autonomously operate in complex real world environments. One of the major reasons for this failure in creating cognitive situated systems is the difficulty in the handling of incomplete knowledge and uncertainty. In this project we are investigating and applying Bayesian models and approaches in order to develop artificial cognitive systems that can carry out complex tasks in real world environments. We are taking inspiration from the brains of mammals including humans and applying our findings to the developments of cognitive systems. The conducted research results in a consistent Bayesian framework offering enhanced tools for probabilistic reasoning in complex real world situations. The performance is demonstrated through its applications to drive assistant systems and 3D mapping, both very complex real world tasks. P. Bessière, C. Laugier and R. Siegwart edited a book titled "Probabilistic Reasoning and Decision Making in Sensory-Motor Systems" [37] which regroups 12 different PhD theses defended within the BIBA and BACS European projects. See: [35], [40], [43], [48], [75], [76], [83], [95], [89].

7.1.3. Intersafe-2

[September 2008 - September 2011]

The INTERSAFE-2 project aims to develop and demonstrate a Cooperative Intersection Safety System (CISS) that is able to significantly reduce injury and fatal accidents at intersections.

The novel CISS combines warning and intervention functions demonstrated on three vehicles: two passenger cars and one heavy goods vehicle. Furthermore, a simulator is used for additional R&D. These functions are based on novel cooperative scenario interpretation and risk assessment algorithms.

7.1.4. sFly ("Swarm of Micro Flying Robot")

[January 2009 - December 2011]

sFly is an European research project involving 4 research laboratories and 2 industrial partners. This project will focus on micro helicopter design, visual 3D mapping and navigation, low power communication including range estimation and multi-robot control under environmental constraints. It shall lead to novel micro flying robots that are:

- Inherently safe due to very low weight (<500g) and appropriate propeller design;
- Capable of vision-based fully autonomous navigation and mapping;
- Able of coordinated flight in small swarms in constrained and dense environments.

The contribution of *e-Motion* to sFly focuses on autonomous cooperative localization and mapping in open and dynamic environments. It started on 01/01/09. For the moment, Alessandro Renzaglia (PhD student) and Agostino Martinelli work on this project. A new Postdoc will be recruited for the project as well quickly.

7.1.5. HAVEit

[February 2008 - January 2011]

European project ICT-212154 HAVEit "Highly Automated Vehicles for Intelligent Transport". (http://www.haveit-eu.org).

HAVEit aims at the realization of the long-term vision of highly automated driving for intelligent transport. The project will develop, validate and demonstrate important intermediate steps towards highly automated driving.

HAVEit will significantly contribute to higher traffic safety and efficiency usage for passenger cars, buses and trucks, thereby strongly promoting safe and intelligent mobility of both people and goods. The significant HAVEit safety, efficiency and comfort impact will be generated by three measures:

- Design of the task repartition between the driver and co-drivingsystem (ADAS) in the joint system.
- Failure tolerant safe vehicle architecture including advanced redundancy management.
- Development and validation of the next generation of ADAS directed towards higher level of automation as compared to the current state of the art.

The contribution of *e-Motion* to HAVEit focuses on safe driving.

7.2. International projects

7.2.1. ICT-Asia "FACT" and ICT-Asia "City Home"

[October 2005-December 2007] and [November 2008 - December 2010]
The Fact project is a joint research project in the scope of the ICT-Asia programme founded by the French Ministry of foreign affairs, the CNRS and INRIA. It aims at conducting common research activities in the area of Intelligent Transportation Systems (ITS). The main objective is to develop new technologies related to the concept of "Cybercar". The project involves the following research teams : e-Motion project at INRIA Rhône-Alpes (leader), Imara project at INRIA Rocquencourt, LASMEA Laboratory at Clermont-Ferrand, SungKyunKwan University (Korea), Shangai Giao Tong University (China), Nanyang Technological University (Singapore) and Tokyo University (Japan). This project has been prolongated by a new project (named "City Home") co-leaded by Ph. Martinet from LASMEA and C. Laugier from e-Motion/INRIA. Several public demonstrations of the results have been performed in France (Clermont-Ferrand) and in China (Shanghai).

7.3. National Collaborations

7.3.1. Collaboration with Institut de la Communication Parlée (ICP)

- Subject 1: Coordination of Orofacial and Gestural Sensori-motor maps Enabling the Emergence of Communication between avatars and Humans. Common PhD thesis and commun publication: [93]
- Subject 2: Théorie de la "langue mère" de Ruhlen. Collaborative work and commun publication: [38]
- Subject 3: Emergence of a language through deictic games within a society of sensori-motor agents in interaction. Common PhD thesis and commun publications: [84], [85]

7.3.2. Collaboration with LPPA-Collège de France

- Subject 1: Bayesian models of superior colliculus, see commun publications: [42] [44].
- Subject 2: Biochemical bayesian computation, see 5.3.3 and common publications: [60]

7.4. International Collaborations

7.4.1. Collaboration with Singapore

e-motion collaborate with the Nanyang Technological University of Singapore (NTU) and the National University of Singapore (NUS) since 1998 (MOU INRIA/NTU, MOU INRIA/NUS, PICS CNRS including the LPPA (College de France, Alain Berthoz), ICT-Asia FACT project and ICT-Asia CITYHOME project) in the framework of the scientific collaboration in the field of autonomous vehicles. This collaboration has brought: (a) an important number of crossed visits and stays (one week to several months) of researchers, (b) Singaporeans students in Inria (level undergraduate to graduate), (c) organization of workshops and (d) postdocs and co-directed PhD students. Brice Rebsamen has defended his PhD Thesis in Singapore in January 2009; Christopher Meng Tay defended his PhD in Grenoble in September 2009. The last workshop of CITYHOME was organized at Bintan (Indonesia) by our NTU partners.

7.4.2. Collaboration with Japan, Korea, China, Taiwan, Vietnam

See the description of the ICT-ASIA “Fact” and “City Home” projects above. The ICT-Asia “PAMM” has been submitted with the university of Taiwan, MICA center of vietnam, SKKU of Korea and university of Kumamoto (Japan). Professor Sukhan Lee visited e-motion in september 2010 for one month.

7.4.3. Collaboration with Spain

E-Motion collaborate with the "Institut de Robotica Industrial" (UPC) in the field of dynamic obstacle detection. The team received Guillem Alenyà at the end of 2008 and two publications have been written in collaboration [31] [32].

7.4.4. Collaboration with Mexico

The thematic network "Image et Robotique" has been implemented from the French-Mexican symposium in Computer Sciences and Control (JFMIA’99) which has been held in Mexico in March 1999. The main goal of this network is to promote and increase the French-Mexican cooperations in Image and Robotics in scientific, academic and industrial fields. This network has been effectively settled in 2000. It supports a yearly school (SSIR http://www.image-and-robotics.org/), students exchange, and crossed visits since 2000 (Prof Enrique Sucar spent a few months at INRIA in 2008 as invited professor). Jorge Rios started his pdD in september 2009. Arturo Escobedo started his phD in december 2010.

7.4.5. Collaboration with Portugal

Partner: University of Coimbra Subject: Bayesian Models for Multimodal Perception of 3D Structure and Motion Collaborative work and commun publications: [50], [88]

7.4.6. Collaboration with Brazil

Collaborative work and ongoing common publications on Bayesian Robot programming with the University of Brasilia. .

7.4.7. Collaboration with Switzerland

Collaborative work and common publications on bayesian Robotics with ETH Zurich. European project framework sFly (further details please find the description of sFly project above) Partner: Autonomous system lab at ETHZ in Zurich

7.4.8. Collaboration with Crete

Subject: European project framework sFly (further details please find the description of sFly project above) Partner: University of Crete (TUC). Collaborative work and staff exchange (Alessandro Renzaglia spent two weeks in July 2009 in TUC)

7.4.9. Collaboration with Italy

Subject: Autonomous navigation in indoor environment Partner: Università Politecnica delle Marche. Common publications [54]

8. Dissemination

8.1. Organization of scientific events

Some members of *e-Motion* participate to the organization of summer schools and conferences:

- C. Laugier participates every year to the organization committees of the major international conference on Robotics, in particular : IEEE International Conference on Robotics and Automation (ICRA), IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), International Conference on Field and Service Robotics (FSR).

- C. Laugier is Profile Editor since 2009 in the IEEE RAS Conference Editorial Board (for IEEE RAS ICRA conference).
- C. Laugier was general chair of IEEE/RSJ IROS'97, Regional Program chair of IEEE/RSJ IROS'00, Program chair of IEEE/RSJ IROS'02, Regional Program Chair of IEEE IV'06, General Chair of the 6th International conference on Field and Service Robotics in 2007, and Program Chair of IEEE/RSJ IROS 2008. He has been program co-chair of IEEE/RSJ IROS 2010.
- C. Laugier has co-organized several workshops on "Safe navigation in Dynamic environments" and on "Intelligent Transportation Systems" in the scope of some major conferences of the domain (IEEE ICRA'05, IEEE ICRA'07, IEEE/RSJ IROS'06, IEEE/RSJ IROS'07, IEEE/RSJ IROS'08, IEEE ICRA'09, IEEE/RSJ IROS'09, IEEE ICRA'10) and in the scope of the ICT-Asia project FACT and the ICT-Asia project CityHome (Seoul 2005, Tokyo 2006, Shanghai 2007, Kobe 2009, Clermont-Ferrand 2009, Bintan Indonesia 2010).

8.2. Books and special issues publications

- Book "Probabilistic Reasoning and Decision Making in Sensory-Motor Systems", Edited by P. Bessière, C. Laugier and R. Siegwart. Springer Tracts in Advanced Robotics (STAR) volume 46, Springer-Verlag, May 2008.
- Special issue of the Journal of Field Robotics (JFR) "Field and Service Robotics", Guest Edited by C. Pradalier, A. Martinelli, C. Laugier, and R. Siegwart. Volume 25, Issue 6/7, July 2008.
- Special issue of the International Journal of Vehicle Autonomous Systems (IJVAS) "Advances in Autonomous Vehicles Technologies for Urban Environment", Guest Edited by D. Wang, S.Sam Ge, and C. Laugier. Volume 6, 2008.
- Special issue of the International Journal of Robotics Research (IJRR) "Field and Service Robotics", Guest Edited by C. Laugier, A. Martinelli, C. Pradalier, and R. Siegwart. Volume 28, Number 2, February 2009
- Special issue of the IEEE Transactions on Intelligent Transportation Systems "Perception and Navigation for Autonomous Vehicles", Guest Edited by C. Laugier, U. Nunes, and A. Broggi. September 2009.

8.3. Academic Teachings

In addition to ponctual academic lectures, the members of *e-Motion* have taught the following lectures:

- Lecture "Robotics Technologies & Applications" (every year since 2000): Europe-France Summer school on "Image and Robotics" (SSIR). *Teacher: C. Laugier.*
- Lecture "Autonomous Robots": International Master MOSIG (M2), INPG, Grenoble, (FR). *Teachers: C. Laugier, O. Aycard, Th. Fraichard, A. Martinelli*. Every year since 2008.
- Lecture "Robotics and Computer Vision": International Master MOSIG (M1), INPG, Grenoble, (FR). *Teachers: C. Laugier, O. Aycard, E. Boyer, E. Arnaud*. Every year since 2008.
- Lecture "Basic tools and models for Robotics" (every year): Cnam Grenoble. *Teachers: C. Laugier and J. Troccaz.*

  Th. Fraichard: Motion Planning course, Master of Science in Informatics at Grenoble (MOSIG), 2nd year, University of Grenoble (FR), Fall 2010.
- Lecture "Knowledge Modelling and Processing": (every year): Master of Computer Science 2nd year, University of Grenoble, (FR). *Teachers: MC. Rousset, J. Gensel, O. Aycard, E. Arnaud*.
- Lecture "Machine Learning": (every year): Master of Computer Science 1st year, University of Grenoble, (FR). *Teachers: E. Gaussier, O. Aycard*.

- Lecture “Machine Learning”: (every year): Master of Computer Science 2nd year, University of Grenoble, (FR). *Teachers: G. Bisson, A. Douzal, A. Guerin, O. Aycard*.
- Lecture “Autonomous Robots”: (every year): International Master of Computer Science 2nd year, University of Grenoble, (FR). *Teachers: C. Laugier, O. Aycard*.
- Lecture “Computer Vision and Autonomous Robots”: (every year): International Master of Computer Science 1st year, University of Grenoble, (FR). *Teachers: C. Laugier, O. Aycard, E. Arnaud, E. Boyer*.
- Lecture “Knowledge Modelling and Processing”: Ecole Polytechnique de Grenoble, filière Traitement de l’Information pour la Santé, University of Grenoble, (FR). *Teachers: D. Ziebelin, and O. Aycard*.
- Lecture “Bayesian techniques in vision and perception”: France-Mexico Summer school on “Image and Robotics” (every year). *Teachers: O. Aycard, E. Sucar*.
- A. Martinelli held a couple of lectures on the behalf of the course “Autonomous Robots” for master students at the ENSIMAG
- A. Martinelli held a couple of lectures on the behalf of the course “Model Identification” for master students at the University of L’Aquila (Italy)
- Lecture A. Martinelli held a couple of lectures on the behalf of the course “Robotics and Computer Vision” for master students at the ENSIMAG
- “Bayesian models of sensory-motor systems” course, Bayesian Cognition winter school. Teacher: P. Bessière

8.4. Consulting

- Pierre Bessière works 20% of his time for the ProBAYES company (http://www.probayes.com) in the scope of a CNRS/Probayes agreement and with the authorization of the French Deontology committee.
- Christian Laugier is a scientific consultant of the Probayes company in the scope of an INRIA/Probayes agreement and with the authorization of the French Deontology committee (since Oct. 2008).

8.5. Conference and workshop committees, invited conferences

- C. Laugier is a member of the steering-advisory committee of IEEE/RSJ IROS (Intelligent Robots and Systems) international conference since 1997. He is also a member of the advisory committee of the ICARCV International conference on Control, Automation, Robotics and Vision.
- C. Laugier is co-chair (with U. Numes and A. Broggi) of the IEEE Technical Committee on “Intelligent Transportation Systems and Autonomous vehicles” (since 2005).
- C. Laugier was the coordinator of the ICT-Asia Network on ITS named FACT including partners from France, Singapore, Japan, Korea, and China (2005-2008). He is now co-coordinator with Philippe Martinet of the new ICT-Asia project “City Home” (2008-2011).
- C. laugier is a member of the permanent organization committee of the Field and Service Robotics Conference (since 1997).
- C. laugier is a member of the editorial board of the journal “Intelligent Service Robotics” (since 2005). He is also a member of the editorial board of the national journal “Revue d’Intelligence Artificielle” (since 1987), and Associate Editor of the journal IEEE Transactions on Intelligent Transportation Systems (since 2008).
- C. laugier co-organized with P. Martinet a workshop at ICRA’10, a special session at ITSC’10 and a special session at ICARCV’10.

- C. laugier is editor at the conference editorial board (CEB) of IEEE RAS for ICRA conference since 2009.

  In 2010, Th. Fraichard served as an Associate Editor for the following major international conferences:

  1. IEEE-RSJ Int. Conf. on Intelligent Robots and Systems (IROS). 2. IEEE Int. Conf. on Robotics and Automation (ICRA). 3. IEEE Intelligent Vehicles Symp. (IV).

  Th. Fraichard also organized the first workshop on "Guaranteeing Safe Navigation in Dynamic Environments". The workshop was part of the 2010 IEEE Int. Conf. on Robotics and Automation (ICRA).
- A Martinelli was a member of the editorial board of the IEEE Transaction on Robotics as Associate Editor (2007-2010)
- A Martinelli and O. Aycard were associate editor for ICRA'11
- Th. Fraichard is a regular member of the programme committees of the ICRA and IROS conferences. He is also Associate Editor for the ICRA 2010 edition.
- A. Spalanzani is member of the editorial committee of the *In Cognito* cognitive sciences journal.
- P. Bessière is a member of the programme committees of the following conferences : Conference ESANN (European Symposium on Artificial Neural Networks), Conference RFIA (Reconnaissance des Formes et Intelligence Artificielle), Conference IEEE/ICRA (International Conference on Robotics and Automation), Conference IEEE/IROS (International Conference on Intelligent Robots and Systems), Conference EA (International Conference on Artificial Evolution)

8.6. Invited talks

- C. Laugier "ICT for improving car safety", Transportation week, Shanghai expo, september 2010.
- C. Laugier "the ICT-car concept", journée INRIA Recherche-Industrie sur le transport, RII Ville durable, juin 2010.
- C. Laugier "TEchnologies for Intelligent Vehicles", invited talk, Alliance MIT-NUS for Future Urban Mobility, National University of Singapore, Dec 2010.
- Th. Fraichard: The Difficulty of Safely Navigating Dynamic Environments, Ariel Univ. Center (IL), Dec. 09.

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