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 NUM

Table of contents

1. **Team** **1**
2. **Overall Objectives** **2**
   2.1. Introduction 2
   2.2. Highlights of the year 2
3. **Application Domains** **3**
   3.1. Introduction 3
   3.2. Future cars and transportation systems. 3
   3.3. Service and intervention robotics. 3
   3.4. Potential spin-offs in some other application domains. 3
4. **Software** **4**
   4.1. Advanced Software 4
   4.2. Old Software 5
5. **New Results** **5**
   5.1. Dynamic World Perception and Evolution Prediction 5
      5.1.1. Visual Dynamic Obstacles detection using Change of Scale 5
      5.1.2. Data-Driven Markov Chain Monte Carlo for Moving Object Tracking 6
      5.1.3. Fast Clustering and Tracking of Moving Objects in Dynamic Environments 8
      5.1.4. Object Extraction using Self Organizing Networks and Statistical Background Detection 9
      5.1.5. Moving Objects' Future Motion Prediction 12
      5.1.6. Interpretation and Prediction in Dynamic Environments 12
   5.2. Localization and Mapping 14
      5.2.1. Simultaneous Odometry and Extrinsic Camera Calibration 14
      5.2.2. SLAM and Cooperative SLAM 14
      5.2.3. 2D/3D efficient environment reconstruction using point-based representation 15
   5.3. Motion planning and Autonomous Navigation in the physical world 15
      5.3.1. Partial Motion Planning 15
      5.3.2. Inevitable Collision States 18
      5.3.3. Trajectory Deformation 20
      5.3.4. Goal oriented navigation in dynamic uncertain environment 22
   5.4. Bayesian Modelling of Sensorimotor Systems and Behaviors 23
      5.4.1. Task Learning for SensoriMotor Based Wheelchair Navigation 23
      5.4.2. Brain Controlled Wheelchair 24
      5.4.3. Bayesian Modelling of Sensorimotor Systems: Application to Handwriting 25
      5.4.4. Models and Tools for Bayesian Inference 27
      5.4.5. Bayesian modelling of the superior colliculus 27
      5.4.6. Biochemical Probabilistic Inference 28
6. **Contracts and Grants with Industry** **28**
   6.1. Cybercars 2 28
   6.2. Profusion 29
   6.3. Toyota Motors Europe 29
   6.4. Denso 29
   6.5. ADT ArosDyn 30
   6.6. LOVe 30
   6.7. sFly "Swarm of Micro Flying Robot" 30
   6.8. HAVEit 30
7. **Other Grants and Activities** **31**
   7.1. European projects 31
   7.2. International projects 31
   7.3. National Collaborations 31

- 7.3.1. Collaboration with Institut de la Communication Parlée (ICP) 31
- 7.3.2. Collaboration with LPPA-Collège de France 31
- 7.4. International Collaborations 32
  - 7.4.1. Collaboration with Singapore 32
  - 7.4.2. Collaboration with Japan, Korea, China 32
  - 7.4.3. Collaboration with Spain 32
  - 7.4.4. Collaboration with Mexico 32
  - 7.4.5. Collaboration with Portugal 32
  - 7.4.6. Collaboration with Brasil 32
  - 7.4.7. Collaboration with Switzerland 32

8. Dissemination **33**
- 8.1. Organization of scientific events 33
- 8.2. Books and special issues publications 33
- 8.3. Visiting scentists in abroad laboratories 34
- 8.4. Academic Teachings 34
- 8.5. Consulting 35
- 8.6. Conference and workshop committees, invited conferences 35
- 8.7. Invited talks 35

9. Bibliography **36**

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2. Overall Objectives

2.1. Introduction

Keywords: *Artificial Perception*, *Autonomous Navigation*, *Bayesian Programming*, *Dynamic World constraints*, *Learning*, *Motion Planning*, *Reasoning under Uncertainty*, *Robotics*.

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 explicitely 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

- Co-organization (with J.P. Merlet of INRIA Sophia-Antipolis ans R. Chatila of LAAS-CNRS) of IEEE/RSJ IROS 2008 conference in Nice (around 1400 participants).
- Publication of the book "Probabilistic Reasoning and Decision Making in Sensory-Motor Systems", P. Bessière, C. Laugier, R. Siegwart.
- C. Laugier invited to be Keynote speaker at the FSR'09 conference (Cambridge).

- Signature of an agreement with Probayes SAS for the valorization of the already patented BOF Technology.
- A. Martinelli has been appointed as an associated editor of the journal IEEE Transaction of Robotics.
- Publication of special issues in the following journals : JFR 2008, IJRR 2009, IJVAS 2008, IEEE Trans on ITS 2009.

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).

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[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, Jean-Marc Bollon.
  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/spip.php?rubrique57) 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 : Christophe Braillon, Amaury Nègre, 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 Occupation 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 Occupation 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 occupation 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.

- *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 differents countries.

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.

- *Grid Occupany 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 Occupany 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 developped 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 preliminay 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. Visual Dynamic Obstacles detection using Change of Scale

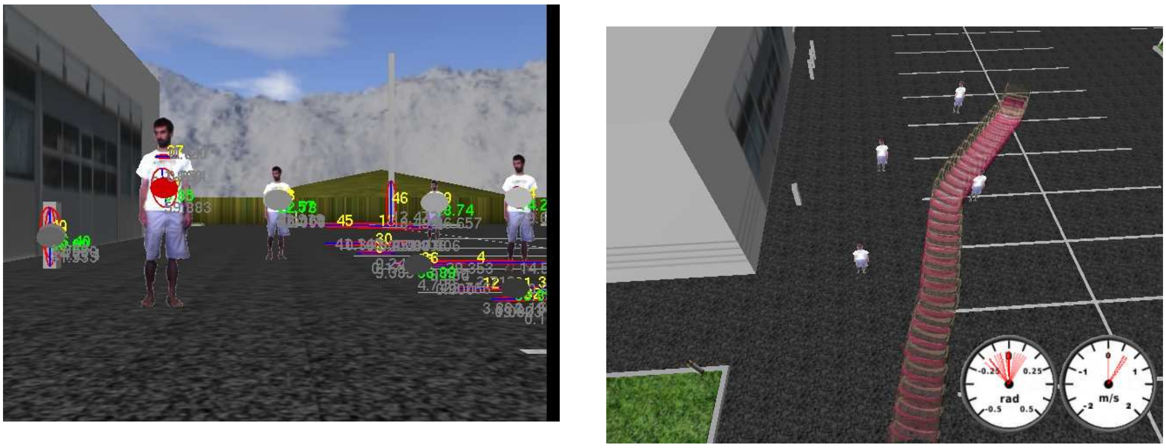
Participants: Amaury Nègre, Guillem Alenyà Ribas, Christian Laugier, Jim Crowley.

To navigate safely in a dynamic environment (with moving pedestrians, vehicles or other obstacles), it is necessary to detect and characterize dangerous objects. In this aim, we developed a visual method that consists in detecting and tracking interesting elements in a camera image and evaluating the time-to-contact to estimate the collision risks.

Our detector extracts ridge segments in a Laplacian Scale Space. Such segments correspond to elongated contrasted areas in the image and are particularly interesting because their describe well object's structure and because the detector is invariant to affine changes. This detector can be define as an extantion of the Laplacian interest point detector as it extracts lines where the Laplacian value is maximum.

After having extracted these ridge segments in a single image, we track them using a particle filter in order to evaluate the motion and the change of scale [28]. Change in scale is known to be used by humans to navigate as a growing motion in the image is related to an approaching motion in the 3D world [92]. Here, we use this change of scale to compute the time to collision (TTC is the time remaining before contact with an obstacle). The TTC computed for each tracked element give us a precious information about their dangerousness of an obstacle (a small positive TTC corresponds to a dangerous approaching obstacle).

Our current work consists in using these tracked features in a reactive navigation framework. The set of tracked objects and their associated TTC is used to define a probability distribution describing the restricted area in the robot commands domain (linear and angular speed). A Bayesian fusion between this distribution and the desired command distribution can then define the final command than is used to control the robot (see Figure 1).



(a) An example of ridge segment tracking and TTC estimation in the camera image (red discs indicate a short TTC).

(b) Vehicle trajectory with obstacle avoidance.

Figure 1. Object tracking for Time-To-Collision estimation and vehicle navigation with obstacle avoidance using position and TTC of tracked ridge segments.

In order to have video rate performance, and so can use our method on line, all algorithms have been implemented on the graphic processor (GPU) which is well adapted to parallel tasks like image processing (Scale space filtering, segment's extraction) and particles filter (each particle can be processed in parallel).

To experiment the visual navigation task, we also designed an artificial landmark very robust and easy to track. This landmark has been used with an autonomous underwater vehicle for docking [10].

This work was done in collaboration with Guillem Alenya of the IRI laboratory (UPC, Barcelona).

5.1.2. Data-Driven Markov Chain Monte Carlo for Moving Object Tracking

Participants: Trung-Dung Vu, Olivier Aycard.

Recent years have seen many research works using laser scanners to detect and track moving objects. On one hand, existing methods usually separate the detection and tracking as two independent procedures, this is what we have done in 2007.

Since detection at one time instant usually results in ambiguities that make the data association become more difficult with missing detections and false alarms. In 2008, we proposed to solve the detection and tracking in a whole process that allows object detection to make use of temporal information and facilitates robust tracking. On the other hand, due to occlusions or laser-absorbed surfaces, an object can be divided into several segments. This makes object detection and tracking much harder when dealing with object merging and track grouping. We introduce a model-based approach and will discuss how using object models to interpret the laser measurements can overcome these problems.

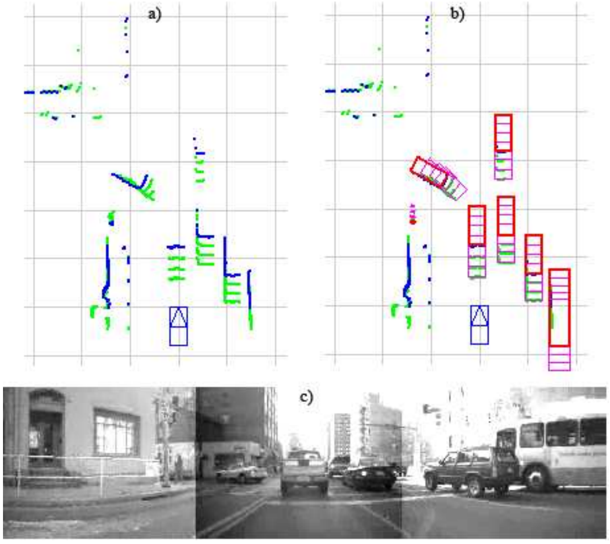


Figure 2. Example of a model-based interpretation of moving objects from laser data. (a) four scans consecutive: in blue is current scan and in green are scans in the past; (b) one possible solution including seven tracks of four cars and one bus represented by red boxes and one pedestrian represented by red dots which are imposed on the range data; (c) situation reference.

We formulate the detection and tracking problem as finding the most likely trajectories of moving objects given laser measurements over a sliding window of time (Fig. 2). An object trajectory (track) is regarded as a sequence of shapes of a predefined model produced in the spatio-temporal space by an object satisfying constraints of the measurement model and the smoothness in motion from frame to frame. In this way, our approach can be seen as a batch method searching the global optimum solution taking into account all past measurements. Due to the high computational complexity of such a scheme, we employ a Data-driven Markov chain Monte Carlo (DDMCMC) method to explore the solution space.

The detection results from our previous works [108] [32] are employed to help driving the DDMCMC search effeciently. The detection results are moving evidences detected based on the occupancy grid constructed around the vehicle. Starting from these identified dynamic segments, by fitting suitable object models to each segment, we generate all hypotheses possibly corresponding to potential moving objects. These rough hypotheses provide initial proposals for the DDMCMC process that performs a finer search over the spatio-temporal space to find the most likely trajectories of moving objects.

The proposed approach is tested on the Navlab datasets [109]. We implement the described algorithm as an online process within a sliding window of 10 frames. From our initial evaluations, the DDMCMC detection and tracking outperforms the detection and tracking using MHT in our previous work [108] [32] in terms of higher detection rates and less false alarms. In addition, with the use of object models, segmented objects caused by laser discontinuities are no longer a problem and tracking results are more accurate. Furthermore, moving objects are naturally classified. The average computational time for the total detection and tracking process is about 60 ms on P4 3.0 GHz PC with unoptimized codes so that it can fulfill the real time requirement (Fig. 3). The result is submitted to ICRA09 [31].

A comparative evaluation of our proposed algorithm with other detection and tracking approaches using MHT is being carried out. We also intend to integrate a road detection procedure in order to provide prior information on moving objects that will certainly improve the effectiveness of the detection and tracking process. An optimization of code to reduce the computational time is ongoing.

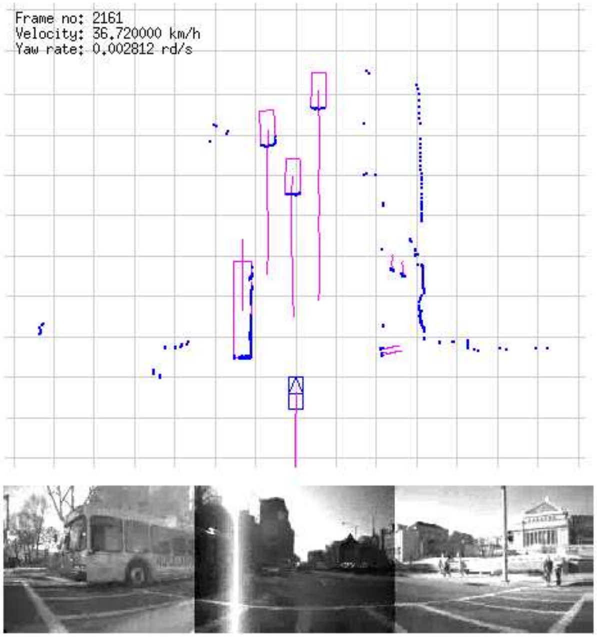


Figure 3. Moving object detection and tracking in action.

5.1.3. Fast Clustering and Tracking of Moving Objects in Dynamic Environments

Participants: Yong Mao, Kamel Mekhnacha, David Raulo, Christian Laugier.

Perceiving of the surrounding physical world reliably is a major demanding of the driving assistant systems and the autonomous mobile robots. The dynamic environment need to be perceived and modeled according to the sensor measurements which could be noisy. The major requirement for such a system is a robust target tracking algorithm. Most of the existing target tracking algorithms [103] use an object-based representation of the environment. However, these existing techniques have to take into account explicitly data association and occlusion problems which are the major challenges of the performances. In view of these problems, a grid based framework, the Bayesian occupancy filter (BOF) [105] [62] has been presented in our previous works.

In the BOF framework, concepts such as objects or tracks do not exist. It decompose the environment into a grid based representation. Thanks to the grid decomposition, the complicated data association and occlusion problems do not exist. Another advantage of the BOF is that the multiple sensor fusion task could be easily achieved. Uncertainties of multiple sensors are specified in the sensor models and are fused into the BOF grid naturally with solid mathematical ground.

Despite of the aforementioned advantages, a lot of applications demand the explicit object-level representation. In our former work, we suggested a hierachical structure where a joint probabilistic data association filter (JPDAF) [103] based object detecting and tracking algorithm was implemented above the BOF layer. However, the computational complexity of this algorithm increases exponentially to the number of objects detected and tracked which prevented it from being applied in the cluttered environment. To overcome this, in 2008 we proposed a novel object detecting and tracking algorithm for the BOF framework [25], [24]. This algorithm takes the occupancy/velocity grid of the BOF as input and extracts the objects from the grid with a clustering module which takes the prediction of the tracking module as a feedback. Thus, the clustering module avoids searching in the entire grid which guarantees the performance. A re-clustering and merging module is employed to deal with the ambiguous data associations. The extracted objects are then tracked and managed in a probabilistic way. The computational cost of this approach is linear to the number of dynamic objects detected, so as to be suitable for scenes in cluttered environment.

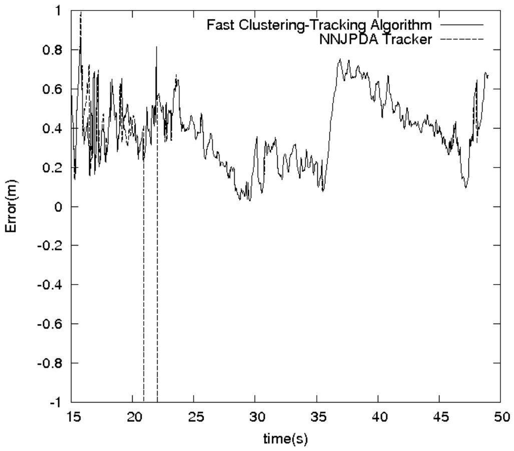


Figure 4. The distance error of the target to the GPS data.

We applied our novel method on the real world experimental dataset collected with the Cycab platform and also on realworld traffic datasets provided by our industrial parners (Denso in particular). Taking the GPS data as the ground truth, we compared our algorithm with the JPDAF based algorithm. Figure 4 shows our method achieved comparable accuracy. Meanwhile, an experiment on simulated data shows the computational cost of our method is 0.0003 seconds per frame and increases linearly with the number of targets in scene. Compared with the NNJPDA algorithm which consumes 0.075 seconds per frame with an average of 11 targets and 18 clusters, but 5 seconds per frame with an average of 22 targets and 28 clusters, our method is extremely effective. Another example of the proposed method is shown in figure 5. These figures illustrate that the BOF based fast clustering and tracking algorithm can detect and track the moving objects consistently and robustly even when occlusions of the targets occur [25].

5.1.4. Object Extraction using Self Organizing Networks and Statistical Background Detection

Participants: Thiago Bellardi, Alejandro Dizan Vasquez Govea, Agostino Martinelli, Christian Laugier.

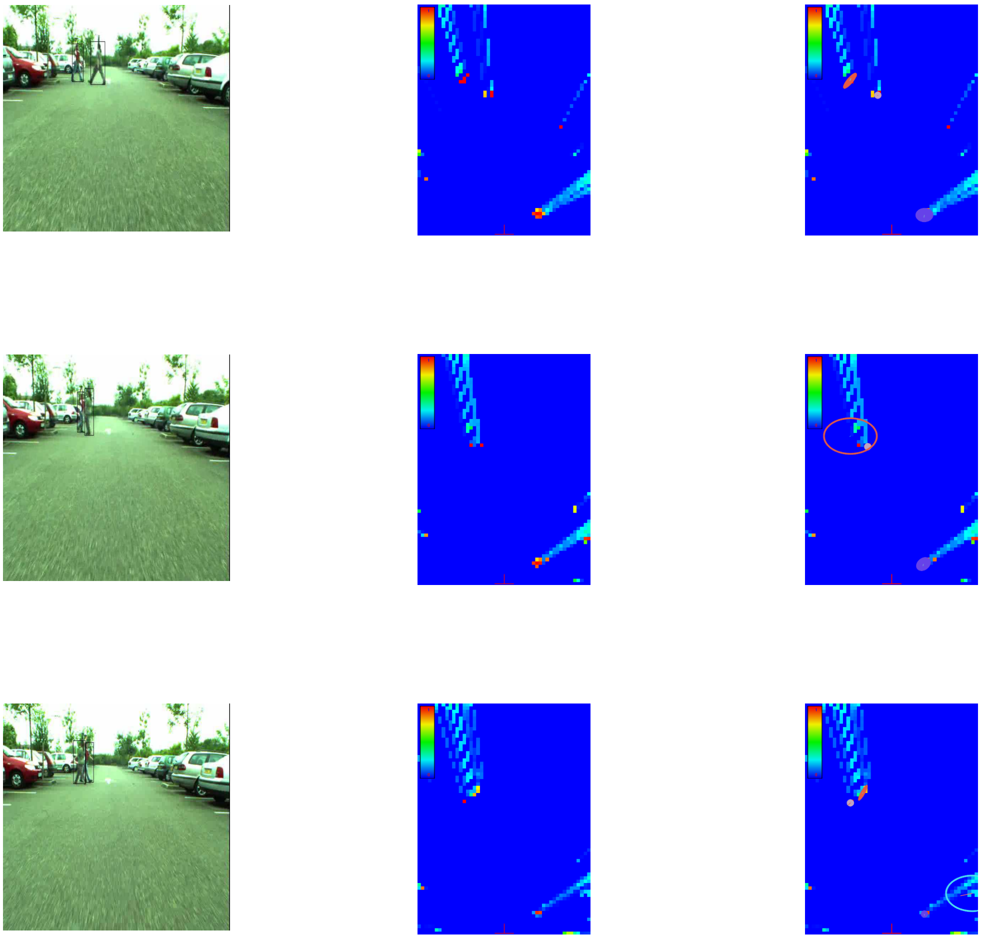
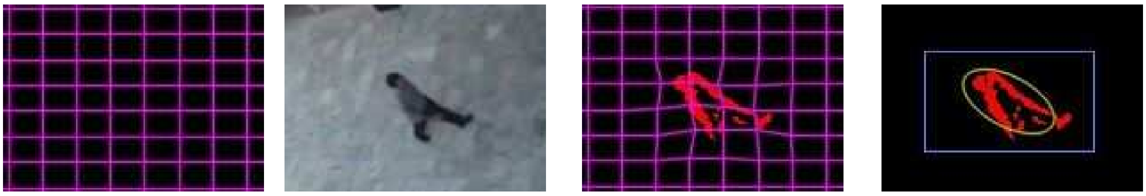


Figure 5. top: The two persons are walking towards each other in the perpendicular direction to the Cycab, middle: An occlusion takes place, Bottom: The occlusion lasts for several frames and finishes.

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* [74] and constitutes an active research domain (see [96]). 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 introduced a novel clustering approach for object extraction based on Self Organizing Networks (SON). We have applied this algorithm to images [106] and occupancy grids [107], and shown that it is able to produce good results in real time. Later improvements in the object extraction algorithm made possible the use of a continuous foreground representation instead of binary. The algorithm complexity is linear in respect to the number of pixels in the image, keeping the capability of processing at the frame rate.



(a) Initial SON (b) Original Image (c) Difference Image and resulting grid (d) Extracted objects

Figure 6. Approach overview. Enlarged views showing the different steps of our algorithm using CAVIAR data.

From 2007 to 2008 we start to focus on the background/foreground classifier exploring the new capability of the extraction algorithm. We implemented a statistical classifier [12], that produces a continuous output between 0 and 1, for each pixel in a frame, corresponding to our believe that the pixel belong to the foreground. Comparing with the previous results, the detections became more robust to noise and we observed less false negative and false positive detections.

(a) Original image (b) Grayscale foreground (c) Detection results

Figure 7. Object detection using the statistical background/foreground classifier. The grayscale foreground is passed as it to the object detector.

Future work includes continuing our experimental work, in particular by improving the background/foreground classifier. Other possibilities include taking into account temporal information by updating the state of the SON when a new input image is available, instead of working in a frame per frame fashion. Finally, we would like to explore the use use of our SON to perform data fusion on a multicamera system.

This work is implied in the BACS project.

5.1.5. *Moving Objects' Future Motion Prediction*

Participants: Alejandro Dizan Vasquez Govea, Thiago Bellardi, Agostino Martinelli, Thierry Fraichard, Olivier Aycard, Christian Laugier.

To navigate or plan motions for a robotic system placed in an environment with moving objects, reasoning about the future behaviour of the moving objects is required. In most cases, this future behaviour is unknown and one has to resort to predictions.

Most prediction techniques found in the literature are limited to short-term prediction only (a few seconds at best) which is not satisfactory especially from a motion planning point of view.

We have first started to explore the problem of medium-term motion prediction for moving objects. As a result, we have proposed a novel cluster-based technique that learns typical motion patterns using pairwise clustering and use those patterns to predict future motion. We have developed a new learn and predict approach which addresses issues that were not solved by our first proposal: (a) Prediction of unobserved patterns and (b) On-line/adaptive learning. The new approach represents motion on the basis of a proposed extension to the well-known Hidden Markov Models framework, that we have named Growing Hidden Markov Models (GHMM). Basically, the extension allows incremental, adaptive, real time learning of the models parameters and structure. Incorporating final positions, objects' goals, in the GHMM state several motion patterns can be represented with a single GHMM.

During 2008, we have performed further experimental validation of GHMMs by comparing them against two state of the art techniques [71], [56]. In our experiments, our approach has exhibited considerably better performance than the other two concerning prediction accuracy and model parsimony. This work has been the subject of an invited journal paper which is now in the review process.

This work is implied in the BACS project.

5.1.6. *Interpretation and Prediction in Dynamic Environments*

Participants: Christopher Tay Meng Keat, Christian Laugier, Chiara Fulgenzi.

A model of dynamic objects at a longer term (usually several seconds) are especially useful in environments where movements of objects exhibit certain structures or motion patterns. In these cases, it is possible to construct motion exemplaires that characterizes the motion patterns which are then used for performing longer term motion prediction. This is performed by construction models of each motion exemplaires and learning the parameters of the models based on data collected from a certain scene. The ability to perform motion prediction on a longer time scale is beneficial for robotic applications such as target tracking or collision avoidance.

Most existing methods in the literature requires a discretization of the state space. To overcome this, in 2007 we proposed a novel [104] motion model based on Gaussian Processes (GP). A GP is a generalization of the gaussian distribution to function spaces where a gaussian distribution is placed on functions. Not only discretization issues are avoided in using GP, it provides a theoretically sound bayesian framework in which one can obtain probability distributions of motion in space as well as a proper way of performing motion prediction in a fully probabilistic manner.

We model the scene using a mixture of GP where each GP represents a motion pattern. The mixture of GP then corresponds to the different motion patterns in a certain scene. An example is shown in figure 8 where the shaded bars represent the covariances of motion patterns and the mean of the of the motion pattern as a red line.

Another advantage of using GP to represent exemplaire paths is the representation of uncertainty in when performing motion prediction. The uncertainty in motion prediction can be simply calculated by marginalizing the gaussian distribution representing the path, given a set of observations. An illustration of the prediction is in figure 9. The figure shows the various GP components corresponding to the predicted paths starting from a certain point. Part of this work is done in the scope of our long-term collaboration with Toyota.

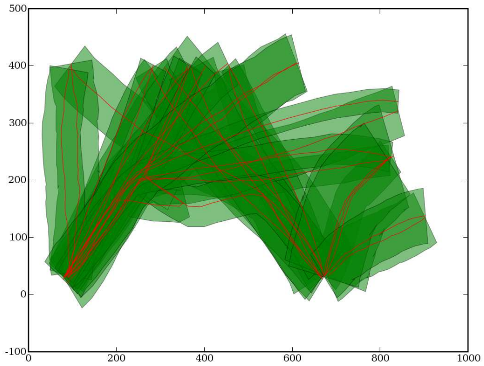


Figure 8. Representations of GP paths. Red lines represent GP mean. Covariances are represented by the green bars

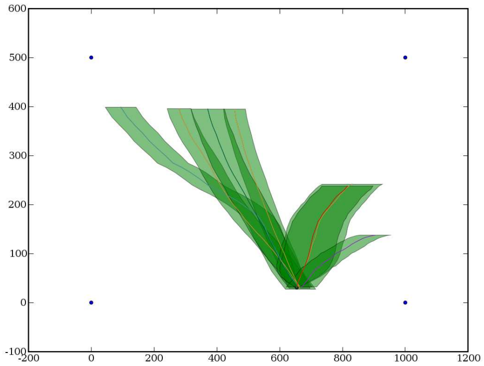


Figure 9. Prediction path means and covariances

As the notion of GPs is able to represent motion patterns in a probabilistic manner, it is thus a natural candidate for applications such as probabilistic motion planning. Such motion planners search for a risk averse motion which avoids potential collisions with dynamic objects in the environment. The GPs are able to give the probability of collision for each considered trajectory by the motion planner. Experimental results have been obtained in 2008 in a joint work [19] (see section 5.3.4) where a Rapidly-exploring Random Tree was used to perform a risk averse motion planning in dynamic environment using the GP predictions to measure the risk of a certain trajectory.

5.2. Localization and Mapping

5.2.1. Simultaneous Odometry and Extrinsic Camera Calibration

Participant: Agostino Martinelli.

This activity is the follow up of a collaboration with the ETHZ in Zurich in the frame-work of the European project BACS. In particular, during the last years, methods to perform on-line sensor calibration have been developed in the frame work of this collaboration [86], [84], [87], [83]. Furthermore, always in the frame-work of this collaboration (in this case also with the help of the BlueBotics company in Lausanne), new methods to extract features from the environment have been introduced [90][30]. During 2008, the problem of sensor self-calibration in mobile robotics by only using a single point feature (e.g. a vertical line) has been considered. In particular, the considered problem was the estimation of the extrinsic parameters of a vision sensor mounted on a mobile platform and simultaneously the estimation of the parameters describing the systematic error in the odometry system. In [22] special attention was devoted to investigate the dependence of the observability properties of these parameters on the chosen robot trajectory. The main contribution provided in [22] was the analytical derivation of the combinations of these parameters which are observable for a given robot trajectory. This derivation requires to perform a local decomposition of the system, based on the theory of distributions. Experiments have also been performed to validate the results.

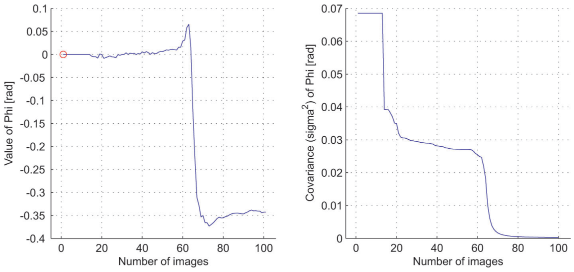


Figure 10. One ofthe estimated parameters describing the extrinsic calibration of an omnidirectional camera mounted on a mobile platform.

Starting from the previous local decomposition, in [9] the observation function has been directly integrated and an analytical expression for this function has been derived. It has been shown that for special trajectories, this observation function is a periodic function whose characteristics (e.g. period, maxima, minima etc.) are simply related to the parameters that have to be estimated in order to perform the calibration. Since the evaluation of these characteristics can be easily done starting from the observation function, a very efficient and powerful approach to perform the calibration has been introduced. Experiments will be performed to validated the approach. Preliminary results are shown in figure 10 where one of the parameters describing the extrinsic calibration of an omnidirectional camera is plotted vs time. This work has been done in the scope of the BACS european project.

5.2.2. SLAM and Cooperative SLAM

Participant: Agostino Martinelli.

This activity is the follow up of the activity carried out since the beginning of 2006 about the problems of simultaneous localization and mapping [82], [80], [85] and cooperative localization [81]. While during 2007 the previous problems have been faced by using a filter approach, a distributed Maximum A Posteriori (MAP) estimator has been introduced in order to better deal with the system non linearities and also to deal with communication issues.

This activity was carried out in collaboration with prof. Stergios Roumeliotis from the Minnesota State University in Minneapolis. In particular, Dr. Agostino Martinelli has spent two months in his lab to acquire the necessary knowledge and to start this collaboration.

As opposed to centralized MAP-based Cooperative Localization, the proposed algorithm reduces memory requirements and computational complexity by distributing data and computations amongst the robots. Specifically, a distributed data-allocation scheme is presented that enables robots to simultaneously process and update their local data. Additionally, a distributed Conjugate Gradient algorithm is employed that reduces the cost of computing the MAP estimates while utilizing all available resources in the team, and increasing robustness to singlepoint failures. Finally, a computationally efficient distributed marginalization of past robot poses is introduced for limiting the size of the optimization problem. Extensive simulations studies validate the performance of the distributed MAP estimator and also compare its better accuracy to that of existing approaches. The main results have been submitted [27]. This work has been done in the scope of the BACS european project. It is also at the heart of our participation into the sFly european project.

5.2.3. 2D/3D efficient environment reconstruction using point-based representation

Participants: Manuel Yguel, Olivier Aycard, Christian Laugier.

In 2007 we have started to explore a new mapping approach that uses a point-based representation that is able to compress the structure of the map. One of the objective was to give a theoretical framework to the point based map. This part is not yet published but already finished and a map reference vector is constituted by a couple formed by a point and a Mahalanobis matrix representing the local shape of the map. In 3D, for instance the map could be locally spherical and the Mahalanobis matrix is the identity for point based landmarks or can be locally planar and the Mahalanobis matrix is $\mathbf{n}\mathbf{n}^T$ where $\mathbf{n}$ is the normal to the plane or the map can be locally linear and the Mahalanobis matrix is $I - \mathbf{u}\mathbf{u}^T$ where $\mathbf{u}$ is a unit vector of the 3D line. The same framework is also valid in 2D, but only spherical and planar Mahalanobis matrices exist.
The other objective was to design a localization algorithm, this part was done and lead to two submitted publications: a conference paper to ICRA 2009 and a journal paper to PAMI in collaboration with the "Perception" EPI. Moreover a research report was published on the subject. The algorithm used is robust and can handle local geometry through the use of Mahalanobis matrices (see fig. 11).

A multi-scale compression framework and a multi-scale localization algorithm have been developped also and presented in the PhD thesis of Manuel Yguel (to be defended at the beginning of 2009). The next steps of this work are: to publish the theoretical framework developped, to develop the theory for hybrid maps based on this framework, to publish the multi-scale compression framework and the multi-scale localization algorithm developped for this map. This work is done is the scope of the BACS FP7 European project.

One other aim of this work is to provide a data-structure that would be efficient to use with fast-slam algorithms where a lot of maps are drawn in a multiple hypothesis framework. This kind of SLAM algorithms, among the top efficient ones, were developped in [89].

5.3. Motion planning and Autonomous Navigation in the physical world

5.3.1. Partial Motion Planning

Participants: Rodrigo Benenson, Thierry Fraichard, Kristijan Macek.

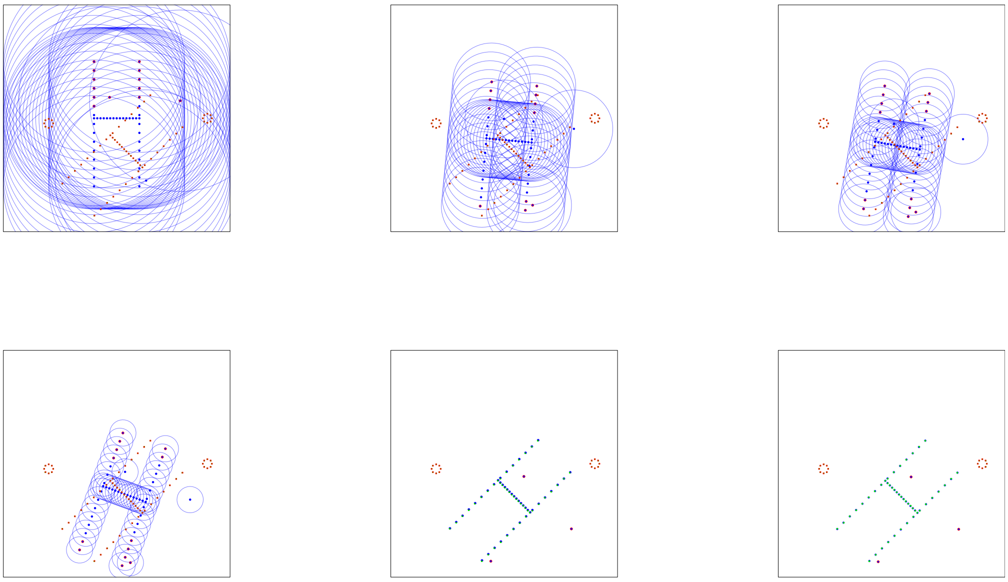


Figure 11. A point registration procedure, a H shape is observed and there is a H shape in the map, however some part of the map blue dots are not observed whereas some part of the observations, the small circles, are not part of the map. Even with those outliers, the pose registration is accurate.

Dynamic environments, *ie* environments with moving objects, impose a strict upper-bound on the time available to a robotic system in order to determine its future course of action. This constraint is henceforth called the **decision time constraint**. The decision time available is a function of what is called the *dynamicity* of the environment which is directly related to the dynamics of both the moving objects and the robotic system. Failure to meet the decision time constraint may put a robotic system in a situation where a collision eventually occurs. Lately, a number of motion planning-based navigation schemes dealing with dynamic environments have been proposed, *eg* [59], [70], [111], [64]. Unlike earlier reactive navigation schemes (that seeks to determine the motion to execute during the next time-step only), they aim at computing a complete motion all the way to the goal. To do so, they rely upon the most efficient motion planning techniques available today, namely randomised techniques such as the Probabilistic Roadmap [72] or the Rapidly Exploring Random Tree [76], whose average running times are low enough so that they can be used on-line. This type of approach is very enticing since it makes up for the lack of lookahead of reactive navigation schemes. However, it is argued that the decision time constraint can be such that it prevents the use of such schemes since the running time of a randomised technique cannot be upper bounded.

Given the intrinsic complexity of motion planning in dynamic environments (see the complexity results established in [101] and [60]), it seems unlikely that a hard decision time constraint could ever be met in realistic situations. We advocate instead the *Partial Motion Planning* principle [94] as a general way to handle the decision time constraint and to address autonomous navigation in dynamic environments. Partial Motion Planning (PMP) is an interruptible planning scheme: when the time available is over, it returns either a complete motion to the goal or a partial motion only, *ie* a motion that may not necessarily reach the goal. This partial motion is then passed along to the navigation system of the robot for execution. Of course, since only a partial motion is computed, it is necessary to iterate the partial motion planning process until the goal is reached. The iterative nature of PMP is doubly required when the robotic system at hand is placed in a uncertain dynamic environment, *ie* an environment for which everything is not known in advance (in particular, the future behaviour of the moving objects). Indeed, motion planning means reasoning about the future. When the future is unknown, one has to resort to predictions, predictions whose validity duration is limited in most cases. An iterative planning scheme permits to take into account the unexpected changes of the environment by updating the predictions at a given frequency (which is also determined by the environment dynamicity). Like reactive approaches, PMP faces two issues, namely the convergence and the safety issues:

Convergence. What guarantee do we have that the goal will ever be reached?

Safety. What guarantee do we have that the robotic system will never found itself in a dangerous situations?

As for the convergence issue, the unrealistic convergence conditions established in [79] leave little hope (it is hardly surprising if the system is placed in an environment with no a priori information about the moving obstacles). To address the safety issue, a solution relying upon the concept of *Inevitable Collision States* is explored (*cf* section 5.3.2). To address the safety issue, different solutions are explored, mainly centered around the concept of *Inevitable Collision States* (*cf* section 5.3.2).

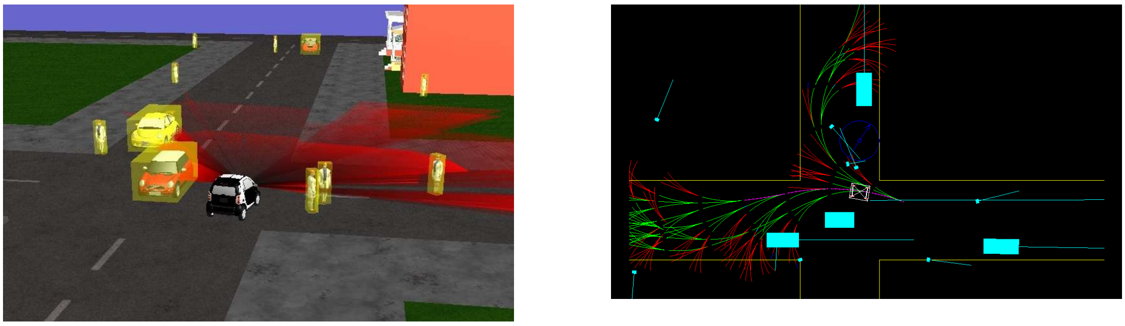


Figure 12. PMP-based navigation in a simulated dynamic environment.

In 2008, work on PMP has mostly been furthered in the scope of the sabbatical stay of Thierry Fraichard at the Swiss Federal Institute of Technology in Zurich (within Prof. Roland Siegwart's group). A PMP module has been developed and integrated in the navigation architecture developed in Zurich. The PMP module is coupled with a route planner and connected with the control, perception and environment modelling modules of the architecture.

Figure 13. The SmartTer experimental vehicle (ETH Zurich).

A diffusion technique is used to build a tree of admissible trajectories embedded in the state×time space of the robotic system and to extract from this tree a partial motion that is used during the next time cycle to drive the system towards its goal. From a theoretical point of view, the safety of the system is guaranteed if and only each partial motion is ICS-free up to the time that corresponds to the initial state of the partial motion that is to be computed at the next navigation cycle), because then, at the next navigation cycle, the navigation module *always* has a safe evasive manoeuvre available. Now, checking whether a given state is an ICS or not requires in theory the *full* knowledge of the environment of and its future evolution. In practice however, one has to deal with the sensors' limited field of views and the elusive nature of the future. Knowledge about the environment of the system is thus limited both *spatially* and *temporally*. This is the very reason why it is impossible to guarantee an absolute level of safety (absolute in the sense that it can be guaranteed that the system will never crash eventually). This intrinsic impossibility compels us to settle for weaker levels of safety. Although weaker, the important thing is that such levels of safety will be guaranteed given the information that the system knows about its environment. We have explored two different levels of safety:

Passive Safety. The first safety level we have seeked to enforce is the simplest one maybe. It guarantees that, should a collision ever occur, the system will be at rest. In other words, if a collision is inevitable, it can be guaranteed that the system always have the possibility to brake down and stop before the collision occurs.

Passive Friendly Safety. In an environment where the moving objects are assumed to be *friendly*, *ie* seeking to avoid collisions, and for which a certain knowledge about their dynamic properties is available, it can be desirable to enforce a stronger level of safety. This second safety level guarantees that, should a collision ever occur, the system will be at rest and the colliding object would have had the time to slow down and stop before the collision had it wanted to.

Other safety levels could be proposed. The ultimate one of course is to determine safety with respect to the set of ICS defined by the current environment model. Given the complexity of characterizing this ICS set, Passive Safety and Passive Friendly Safety constitutes interesting alternatives in the sense that they can be computed efficiently and provide an adequate level of safety. Fig. 12 illustrates PMP-based navigation in a simulated dynamic environment. This work has already yielded two publications in international conferences [21], [20] Experiments with the SmartTer platform (Fig. 13) are underway. They will be documented in Kristijan Macek's Ph.D thesis.

5.3.2. Inevitable Collision States

Participants: Thierry Fraichard, Luis Martinez-Gomez.

Autonomous mobile robots/vehicles navigation has a long history by now. Remember Shakey's pioneering efforts in the late sixties [91]. Today, the situation has dramatically changed as 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 (11 self-driving and 50 human-driven). 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?). Another point worth mentioning is that at least one collision took place between two competitors. It raises the important issue of *motion safety*, *ie* the ability for an autonomous robotic system to avoid collision with the objects of its environment.

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 [67], (ii) car-like vehicle moving in a roadway-like environment [94][2], (iii) spaceship moving in an asteroid field [61]. In all

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

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.

Since 2007, we have been working on *generic* and *efficient* ICS-Checker for planar robotic systems with arbitrary dynamics moving in dynamic environments. The efficiency is obtained by applying three principles: (a) reasoning on 2D slices of the state space of the robotic system, (b) precomputing off-line as many things as possible, and (c) exploiting graphics hardware performances. A preliminary version of the ICS-Checker was presented at the 2007 IEEE Int. Conf. on Robotics and Automation (ICRA) [93]. A final version have been presented in 2008 at the IEEE-RSJ Int. Conf. on Intelligent Robots and Systems (IROS) wherein the ICS-Checker was applied to two different robotic systems: a car-like vehicle and a spaceship.

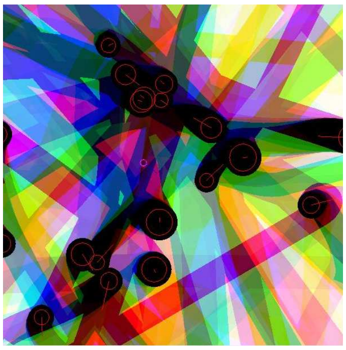


Figure 14. ICS-AVOID *in action: the black regions are forbidden states (ICS).*

Next, we moved to design 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. To that end, the ICS-Checker proposed in [23] is used. This collision avoidance scheme, henceforth called ICS-AVOID, *guarantees motion safety with respect to the model of the future which is used*. To demonstrate the efficiency of ICS-AVOID, it has been extensively compared with two state-of-the-art collision avoidance schemes, both of which have been explicitly designed to handle dynamic environments. The first one has been proposed by [102] and is a straightforward extension of the popular Dynamic Window approach [66]. The second one builds upon the concept of Velocity Obstacle concept [65].

If ICS-AVOID were provided with full knowledge about the future, it would guarantee motion safety no matter what. Given the elusive nature of the future, this assumption is unrealistic. In practice, knowledge about the future is limited. However, the results obtained show that, when provided with the same amount of information about the future evolution of the environment, ICS-AVOID performs significantly better than the other two schemes. The first reason for this has to do with the respective time-horizon of each collision avoidance scheme thus emphasizing the fact that, reasoning about the future is not nearly enough, it must be done with an *appropriate* time horizon. The second reason has to do with the decision part of each collision avoidance scheme. In all cases, their operating principle is to first characterize forbidden regions in a given control space and then select an admissible control. Accordingly motion safety also depends on the ability of the collision avoidance scheme at hand to find a such an admissible control. In the absence of a formal characterization of the forbidden regions, all schemes resort to sampling (with the inherent risk of missing the admissible regions). In contrast ICS-AVOID, through the concept of *Safe Control Kernel*, is the only one for which it is guaranteed that, if an admissible control exists, it will be part of the sampling set (thus guaranteeing safe transitions between non-ICS states). A paper describing the results of this comparison has been submitted to the 2009 IEEE Int. Conf. on Robotics and Automation (ICRA).

5.3.3. Trajectory Deformation

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

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 [78]. 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.

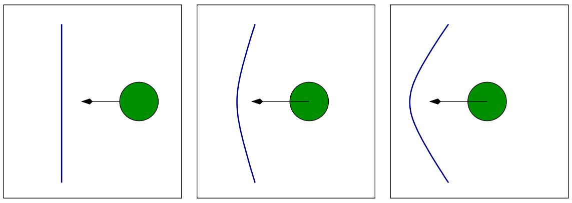
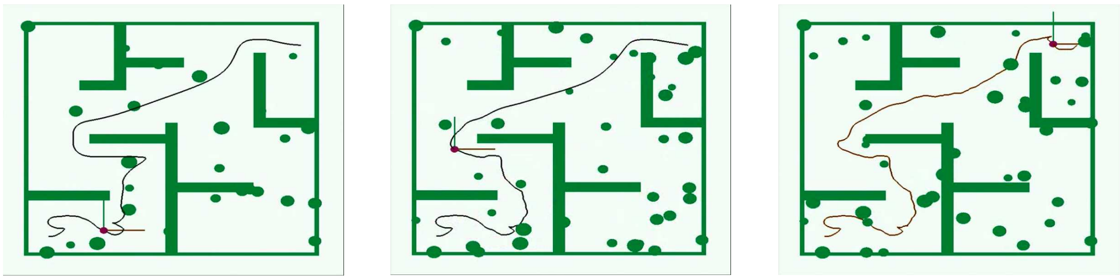


Figure 15. Path deformation problem: in response to the approach of the moving disk, the path is increasingly deformed until it snaps.

The different motion deformation techniques that have been proposed [97], [73], [58], [77], [110] 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. For instance in a scenario such as the one depicted in Fig. 15, it would be more appropriate to leave the path as it is and adjust the velocity of the robotic system along the path so as to avoid collision with the moving obstacle (by slowing down or accelerating). 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. Unlike path deformation wherein spatial deformation only takes place, trajectory deformation features both *spatial and temporal* deformation meaning that the planned velocity of the robotic system can be altered thus permitting to handle gracefully situations such as the one depicted in Fig. 15.

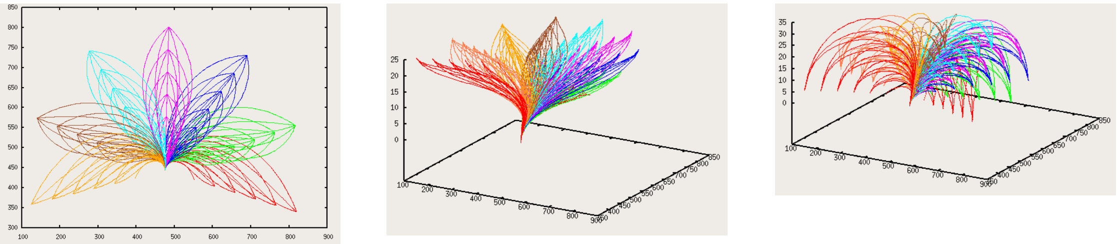


(a) t = 5 (b) t = 20 (c) t = 30

Figure 16. Double Integrator system: the snapshots depicts the path at different time instants ($x \times y$ view).

In 2007, we presented the first trajectory deformation scheme [75]. It operates in two stages (collision avoidance and connectivity maintenance stages) and is geared towards manipulator arms. Since then, we have been working on a novel trajectory deformation scheme, henceforth called `Teddy` (for Trajectory Deformer). It operates in one stage only and is designed to handle arbitrary robotic systems. `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.

`Teddy` was initially developed in the scope of the Master's thesis of Vivien Delsart [63] that addressed the case of a double integrator system (linear dynamics). This work was presented at the 2008 EUROS Conference [17] and yielded a journal article due to appear in 2009 [6]. Results of the trajectory deformation process are depicted in Fig. 16.



(a) $x \times y$ view (b) $x \times y \times t$ view (c) $x \times y \times v$ view

Figure 17. Steering method: examples of trajectories generated for different goal state-times.

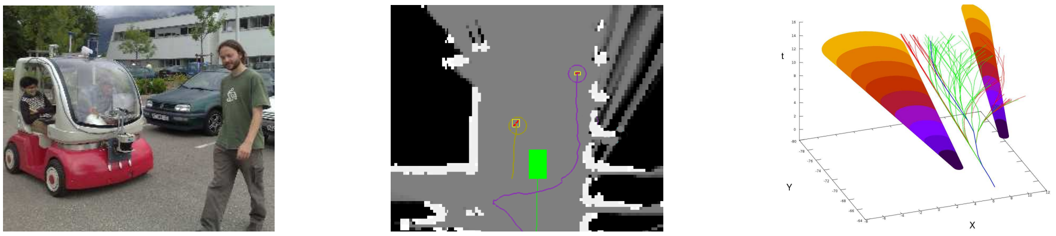
In 2008, we have studied the case of a car-like system (non-linear dynamics). The computation of the internal forces for such a system becomes complex since it requires the characterization of its set of reachable states, complex to the point that it may be incompatible with the real-time requirements of a dynamic environment. To solve this problem, we have decided instead to base the internal forces computation upon a *steering method*, *ie* a function that computes a feasible trajectory between arbitrary pairs of states. To that end, we have developed a novel steering method derived from that of [69]. Unlike standard steering methods, ours must be able to compute feasible trajectories between states with a fixed time component. Examples of the trajectories generated are depicted in Fig. 17. This work yielded a presentation at the 2008 Int. Conf. on Intelligent Robots and Systems (IROS) [16] and a submission at the 2009 Int. Conf. on Robotics and Automation (ICRA).

5.3.4. Goal oriented navigation in dynamic uncertain environment

Participants: Chiara Fulgenzi, Christopher Tay Meng Keat, Anne Spalanzani, Christian Laugier.

The problem of autonomous navigation in dynamic environment is a real challenge for nowadays robotics. Many techniques have been developed to address navigation in known static environment (path planning algorithms) and for exploration tasks. In dynamic environment, the developed approaches are usually based on reactive algorithms which make the assumption that the local environment is perfectly known and that use a static representation that is updated on-line with the new observations. A minor part of reactive techniques (Velocity Obstacles [68] [65] and Dynamic Object Velocity) and partial planning take explicitly into account the fact that the obstacles are moving and make the hypothesis that the robot knows exactly the trajectory of this last ones. Our aim is then to put in relation the decision about motion and the on-line uncertain perception of the world: the uncertainty and incompleteness of the information of the static and dynamic world cannot be ignored and is not possible to compute a full plan in advance.
At first we focused our attention on a reactive method based on the Velocity Obstacle approach. We developed a novel technique and integrate the velocity obstacles with a probabilistic perception of the occupation of the space and of the velocity of the obstacles. A space-time occupancy grid estimates the occupation of the space and a probability distribution over velocities for each object in the environment; the probability of collision in time can be estimated and a safe control is chosen. The algorithm takes into account uncertainty coming from sensors limited range and error probability, occluded space, uncertain velocity estimation, unknown obstacle shape. Our results were published at ICRA 2007 [68] and used in the LOVe project.
These last two years we worked with the purpose to develop a more complex navigation structure which could integrate medium-term prediction, short-term prediction and reactive behaviour. While reactive behaviour is based on the previously described algorithm, short-term and medium-term prediction are used within a partial planner which takes into account the different accuracy and reliability of prediction to find safe control sequences. We developed a search method which is a novel extension of the Rapidly-exploring Random Trees algorithm for the case of probabilistic uncertainty. For each partial path searched, a probability of success is computed on the basis of the environment information and probabilistic prediction. The search is biased not only by the goal direction but also by the likelihood of the paths. This search method has been integrated with a partial planning algorithm, which accounts for safety issues and chooses an output partial path. Short-term predictions are given by a multi-target tracking algorithm. These predictions are reliable only within a short period and are represented by one or more Gaussians (respectively in the case of Kalman Filter tracking or of Multi Hypotheses Tracking) with covariance growing in time. We tested the partial planner with real data acquired with the Cycab (Fig. 18(a)); The environment is observed with a laser range finder: the static environment is mapped in an occupancy grid, while moving pedestrians are tracked with a Kalman filter (Fig. 18(b)); our navigation algorithm searches the space and provides a safe partial path: in Fig 18(c) the cones represent the 1 standard deviation ray uncertainty in obstacle prediction, the green and red lines represent the partial paths explored and a threshold has been applied to show safe and unsafe nodes. The blue line is the chosen path. The partial paths issued at each timestep have been then tested with the real observations acquired and have been proved to be consistent with the predictions.

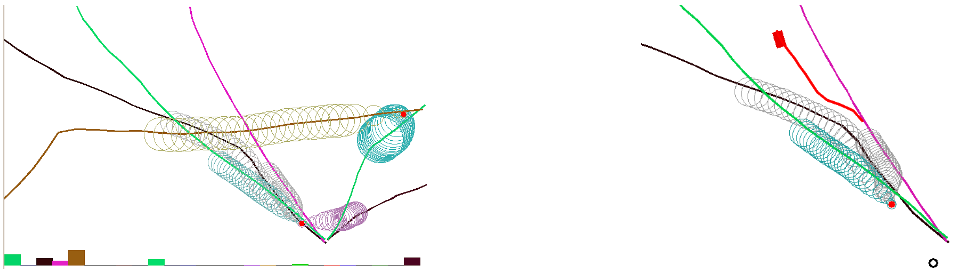
However, the motion model estimated by the tracking is valid only in a short-time period. So, medium-term prediction is based on pre-learned typical patterns. The moving obstacles are supposed to be intelligent agents moving with the intention to reach a specific goal. With this hypothesis it is possible to observe the environment in order to learn the typical behaviour of the obstacles and predict their future motion with a certain confidence. We consider that the system has already learnt a set of typical patterns. We integrated our search algorithm with two different representations of typical patterns developed in the team: Markov graphs by Dizan Vasquez [11] and Gaussian Processes by Christopher Tay (see section 5.1.6). In the case of Markov graphs, the obstacles trajectories are represented by discrete nodes and the prediction is made estimating the state of the obstacle and letting the graph evolve. For each future time step a discretized distribution is obtained, represented by a set of particles with weight proportional to their probability. In the case of Gaussian Processes representation,



(a) (b) (c)

Figure 18. (a) Estimated occupancy grid and tracked pedestrians; (b) The prediction, the searched space and the path chosen; (c) Test of a partial path with the real observation.

obstacles trajectories are represented by continuous functions each characterised by a mean function and a covariance function. To predict the future state, the sequence of observations is considered and the probability that an object is following one or the other pattern is estimated. The probability distribution is so given by a Gaussian mixture at each time instant. Differently from the Multi Hypothesis Tracking, the Gaussians do not grow indefinitely with time, but follow the typical patterns (Fig. 19(a)). Our algorithm is able to integrate these different kinds of predictions and to update on-line the probabilistic information to give a safe an goal solution with the current information. These algorithm have been tested on the Cycabtk simulator with real and simulated trajectories acquired in collaboration with Dizan Vasquez and Christopher Tay (Fig. 19(b)). Our results have been published in IROS 2008 ([19])



(a) (b)

Figure 19. (a) Typical patterns represented by Gaussian Processes and predictions of two moving obstacles. (b) The prediction for a moving obstacle and the partial path chosen.

This work is supported by a grant from the European Community under the Marie-Curie project VISITOR and implied in the LOVe and BACS projects.

5.4. Bayesian Modelling of Sensorimotor Systems and Behaviors

5.4.1. Task Learning for SensoriMotor Based Wheelchair Navigation

Participants: David Partouche, Anne Spalanzani, Christian Laugier.

The goal of this project is to have a robotic wheelchair being able to autonomously navigate in an indoor dynamic environment. The robot learns to navigate by observing the instructor trying to reproduce and generalize the given task. To reach this goal, many points have to be settled: how the user and the robot communicate, what is a simple behavior, how complex behaviors can be created combining simple ones, how associate a behavior to a task.

In 2007, a list of behaviors to be learnt have been identified, and clustered in three groups: reflex (collision, wandering...), reactive (obstacle avoidance, wall following...) and cognitive (human tracking, path following ...) behaviors. Some of these behaviors have been implemented using Fuzzy Neural Networks.

In 2008, Growing Hidden Markov Models (GHMM) have been used to generate sequences of behaviors [11]. Each node in the GHMM represents a behavior, and the behaviors are linked between them in a temporal order. For a behavior to occur, the robot must have executed the precedent behaviors already. Each behavior can be linked to one or more behaviors, and each link has a probability to be used, the probability will depend of the past behaviors the robot executed. These probabilities are calculated during learning, observing which behavior the instructor is using the more often.

Experiments have been initiated for a very simple environment (a corridor going to a rectangular room). The robot starts in the corridor, and then the user drives the robot through the corridor, then crosses the room by following the wall on its right side. The goal of this experiment is to choose, from a set of 4 hardcoded behaviors (fuzzy systems incoding: corridor following, left wall following, right wall following, goal reaching), two different behaviors needed to solve the task: corridor following and right wall following. The interaction is done via a poor interface. A map of the environment is presented to the user, who can then click directly on the map to control the robot. A module with an obstacle avoidance system controls the robot for reaching the goal. Once the instructor has shown the task to be accomplished, the system must be able to analyze these instructions. The first step is to decouple this complex task into a sequential list of more basic behaviors. Once the task has been segmented, we have to recognize the behaviors used during the task. The behaviors are encoded in a fuzzy system and new behaviors are learned by the GenSoYager-FNN, a fuzzy neural network developed at the Center for Computational Intelligence (C2I, http://www.c2i.ntu.edu.sg). We are actually developing the behavior recognition algorithm.

This work is implied in the BACS project.

5.4.2. Brain Controlled Wheelchair

Participants: Brice Rebsamen, Christian Laugier.

This work has been done at the NTU of Singapore and in cooperation with the NUS Singapore. It is also implied in the BACS project. A brain-computer interface (BCI) is a system that allows direct control of a computer by thought. BCIs have the potential to help people with various disabilities, e.g. individuals suffering from amyotrophic lateral scleroses (ALS), severe cerebral palsy, head trauma, multiple sclerosis, and muscular dystrophies, to communicate or perform ordinary tasks. BCI applications range from typing words, moving a cursor over the screen, gaming, or controlling a TV.

Robotic applications are a different story: controlling a robotic device, such as a wheelchair or a prosthesis, requires continuous and accurate commands. However, due to the poor and noisy signal, information from BCIs can typically be extracted only at a very slow pace (up to several seconds), or with a very high uncertainty. A solution to this conflicting situation is to endow the system with enough autonomy to avoid dangerous situations.

Hence, in [95], an EEG BCI based on recognition of three mental states (providing frequent signals but with a relatively low confidence) interacts continuously with automatic behaviors of an autonomous robotic wheelchair to successfully maneuver in the environment. However, this approach requires the user to be constantly alert, which is likely to cause stress.

Our solution [100] relies on motion guidance and destination selection: virtual guiding paths connect locations of interest in the environment (see figure 22). These paths can be traced automatically if an accurate map of the environment is available, or manually by simply pushing the wheelchair once along the desired trajectory.

Once a network of guiding paths is available, navigating in the environment simply consists in selecting the desired destination.

For destination selection we use a BCI based on the P300 signal. The user focuses his or her attention on an item within a list of 20 or more while the items are presented in random order (see figure 21). A peak of potential appears in the EEG about 300ms after the item of interest was presented (see figure 20). Upon detection of the P300 signal, the target is traced back as the item that was presented 300ms earlier. For greater accuracy and reliability the process can be repeated several times. Typically, this kind of interface can achieve a response time in between 10 to 20 seconds with an accuracy close to 100%.

This strategy has the important benefit of requiring minimal input from the subject, therefore minimizing concentration effort, thus fatigue. Moreover, since the trajectories are repeated over time, the predictability of the motion adds confidence in the machine. Lastly, because no complex sensor is required to perceive and interpret the environment, the price of the robotic system is very low, thus allowing a larger number of disabled to afford it.

Two faster BCIs were developped for issuing stop commands within a few seconds. The first one is a modified version of the P300 selection interface: only one out the nine buttons is active (the stop button). With this configuration the false acceptance rate is greatly reduced, thus allowing to reduce the P300 detection threshold, thereby reducing the response time [98]. The second stop interface relies on a different brain signal: by imagining left or right limb movements, subjects can modify synchronization of the μ and β rhythms in the pre-motor cortex. This type of interface is typically used for 1D or 2D control of a cursor on screen. In our configuration, a stop command is issued when the amount of $\mu\beta$ desynchronization goes beyond a certain threshold. Visual feedback can be provided in the form of a cursor moving left or right proportionally to the amount of desynchronization.

Both interfaces yield a similar response time (approximately 5 seconds) but they have their pros and cons: the P300 stop interface is easy to use but suffers from a relatively high false positive rate (1.3 per 100 seconds); the $\mu\beta$ interface does not suffer from any false positive, however it is relatively difficult to use and may require a long training. It therefore left to the user to decide which interface is more suitable according to his ability.

The slow but accurate P300 selection interface is combined with one of the two interfaces for stopping to form an hybrid BCI. Switching between modalities is controlled by a simple state machine as illustrated on figure 23.

This work led to the following publications [99], [100], [98] as well as a PhD thesis [1].

5.4.3. *Bayesian Modelling of Sensorimotor Systems: Application to Handwriting*

Participants: Estelle Gilet, Pierre Bessière, Julien Diard.

The goal of the PhD of Estelle Gilet, is to define a Bayesian model of the whole sensorimotor loop involved in handwriting, from visual sensors to the control of the effector [35]. We aim to implement a simulation of handwriting based on three points: the perception, the representation and the production of letters.

In 2007, we studied the state-of-the-art of the modeling of sensorimotor systems, focusing more precisely on handwriting movements. We focused on the state-of-the-art of the perception of hand trajectory and we examined studies of the kinematic and dynamic aspects of human arm movements.

In 2008, we focused on how the central nervous system represents the sensorimotor plans associated with writing movements. In the motor theories of perception, the perception and the production share the same set of invariants and they must be linked. The model is structured around an abstract internal representation of letters, which acts as a pivot between motor models and sensors models. We assume that a letter is internally represented by a sequence of viapoints, that are part of the whole X, Y trajectory of the letter. We restrict via-points to places in the trajectory where either the X derivative or the Y derivative, or both, are zero. The representation of letters is independent of the effector usually used to perform the movement.

Figure 20. (left : Photograph of the prototype brain controlled wheelchair based on a standard powered wheelchair. A laptop is connected in between the joystick and the power drivers, and rotary encoders mounted on glide wheels fixed below the seat are used for odometry. right :The top panel shows the raw EEG signal from ten electrodes. The vertical lines mark the times of stimuli, the red line corresponding to a target stimulus. Bottom: when several epochs are averaged, uncorrelated noise is canceled out; the EEG signal shows a potential peak 300ms after the target is presented (red curve), whereas it remains relatively flat at other times or when other items are presented (green curve).

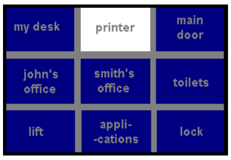


Figure 21. Context dependent menu for selection of the next move. When the wheelchair reaches a destination, the commands displayed to the subject are updated to the new destination. Note that the number of commands is not limited to nine: in can be on the order of tens.

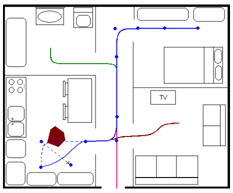


Figure 22. Example of a map with guiding path in a home environment. The paths are defined by a small number of control points which have a clear geometric meaning as attraction points of a B-splines, and can be used to modify the path. For example the figure shows how the path in the kitchen is modified to avoid a large object which makes obstacle.

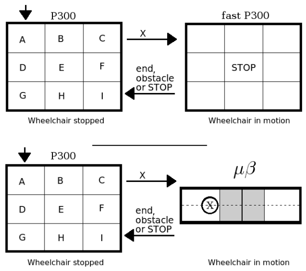


Figure 23. The P300 destination selection interface and the stopping interface are used alternatively. The stopping interface can be either the fast P300 stop BCI (top), or the $\mu\beta$-BCI (bottom) depending on user preference.

The sensor model (vision) concerns the extraction of via-points from trajectories, using their geometric properties. The motor model concerns general trajectory formation. It is expressed in a cartesian reference frame. An acceleration profile is chosen, that constrains the interpolation. In our case, we used a bang-bang profile, where the arm first applies a maximum force, followed by a maximum negative force. The effector model is made of two parts, related to the geometry of the considered effector (kinematic model) and the control of this effector for general movement production (dynamic model).

Thanks to Bayesian inference, the joint probabilistic distribution can be used to automatically solve cognitive tasks. We define a cognitive task by a probabilistic term to be computed, which we call a question. Our model allows to solve a variety of tasks, like letter reading, recognizing the writer, and letter writing (with different effectors).

This work is done under the joint supervision of Pierre Bessière and Julien Diard of the LPNC laboratory (Laboratoire de Psychologie et NeuroCognition, CNRS, Grenoble). Is is implied in the BACS european project.

5.4.4. 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 [88] [14]. 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/spip.php?rubrique57). 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 effectuated taking into account the goals of the BACS project partners.

5.4.5. Bayesian modelling of the superior colliculus

Participants: Pierre Bessière, Francis Colas.

Among the various possible criteria guiding eye movement selection, we investigate the role of position uncertainty in the peripheral visual field. In particular, we suggest that, in everyday life situations of object tracking, eye movement selection probably includes a principle of reduction of uncertainty.

To do so, we confront the movement predictions of computational models with human results from a psychophysical task. This task is a freely moving eye version of the Multiple Object Tracking task with the eye movements possibly compensating for lower peripheral resolution.

We design several Bayesian models of increasing complexity, whose layered structures are inspired by the neurobiology of the brain areas implied in eye movement selection.

Finally, we compare the relative performances of these models with regard to the prediction of the recorded human movements, and show the advantage of taking explicitly into account uncertainty for the prediction of eye movements.

This work as been done in collaboration with LPPA-Collège de France and with the Max Planck Institute in Tuebingen. A common publication in Biological Cybernetics (in press) describes this work in details [5].

5.4.6. Biochemical Probabilistic Inference

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.

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. 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.

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.

To prove this hypothesis, we plan to develop: 1. A comprehensive and coherent formalism to handle both macroscopic and microscopic levels of description, 2. A software package to emulate complex biochemical interactions and to demonstrate the plausibility of our working hypothesis.

Finally, we wish to explore, through the search for new partners for future projects, the possibility to design artificial systems mimicking the biochemical interactions and working on similar principles and nanoscale space-time grain. In the future, this could open the way to the development of revolutionary probabilistic machines. An ADR proposal has been submitted on this topic.

6. Contracts and Grants with Industry

6.1. Cybercars 2

[January 2006-December 2008]

European project IST Cybercars 2, “Close Communications for Cooperation between Cybercars”.

(http://www.cybercars.org).

This Project is driven by the vision that, in the short term future, Cybernetic Transport Systems (CTS) based on fully automated urban vehicles (the cybercars) will be seen on city roads and on new dedicated infrastructures. Such systems have been developed and evaluated in the scope of the CyberCars (http://www.cybercars.org) and CyberMove (http://www.cybermove.org) projects of the 5th FWP and are now being deployed. However, presently these CTS can only operate in low demand environments where little interaction between vehicles is anticipated. In order for these systems to address high demands, more cooperation between vehicles is needed. This is the topic of this Project, based on vehicle-vehicle and vehicle-infrastructure communications and vehicles coordination. We will address in particular the cooperation between vehicles running at close range (platooning) and at intersections (merging, crossing). The contribution of *e-Motion* to Cybercars 2 focuses on cooperative driving.

6.2. Profusion

[February 2004-April 2008]

European project, PreVENT Programme (Preventive and Active Safety Applications) Profusion, “Project for Robust and Optimized Perception by Sensor Data Fusion”. The goal was to develop new concepts, methods and theories for sensor data fusion for Automotive Industry. These solutions allow to perceive the environment surrounding a car and automatically build a model of this environment. This model will be interpreted in order to assist the car driver. The resulting prototypes have been tested and validated on European car demonstrators (on a Volvo truck and a Mercedes-DaimlerChrysler car). The Profusion phase2 consortium is constitued of 10 european car manufacturers, suppliers and research institutes: (BMW, CRF, DaimlerChrysler, Delphi, Forwiss, ICCS, INRIA, Sagem, TUC, Volvo).

6.3. Toyota Motors Europe

[Feb 2006 - Jan 2009]

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.

6.4. Denso

[Sept 2007 - Sept 2008]

Industrial contract “Application of Bayesian Occupancy Filter technology to DENSO LIDAR data” involving INRIA, Denso and Probayes.

This contract is the follow up of a previous contract signed in 2006 by Denso and INRIA for evaluating the applicability of the “Bayesian Occupancy Filtering” (BOF)[3] technology on Denso Lidar data. After having tested during four months the produced software on a Lidar mounted on a vehicle, Denso has proposed a second contract for completing the software. The main functionnalities studied in this second contract concern the clustering of the detected obstacles points (using both position and velocity data), and the study of the effects of the ego-motion parameters. The next collaboration topic is currently under discussion with Denso.

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[3] The BOF has initially been developed by INRIA (see C. Coué Thesis and related INRIA publications); then, it has been improved in collaboration with the Probayes company, and patented in 2006.

6.5. ADT ArosDyn

[Nov 2008 - Oct 2011]

Technological Development Action (ADT) supported by INRIA DDT (Direction of the Technological Development). This project involves the following partners: EPI e-Motion (C. Laugier is the coordinator), EPI Perception (E. Boyer), SED Rhône-Alpes; it also involve individual collaborators (E. Malis from EPI Arobas and J. Crowley from EPI Prima) and a spin-off company (Probayes). Some international companies of the automotive domain are also involved has potential customers for the produced technologies.

The main objective of ArosDyn is to develop an embedded system for robust dynamic scene analysis and danger assessment in road and urban traffic situations. This system will be used in the scope of a Driver Assistance System.

6.6. LOVe

[December 2005-December 2009]

National project, Predit Programme LOVe "Logiciel d'Observation des Vulnérables". (http://love.univ-bpclermont.fr/) The goal of this project is to develop new methods and prototypes for improving vulnerable security and car driver's confort. Artificial perception algorithms will be developped for the localization of the road and for the detection, localization, recognition and tracking of mobile objects using different kind of sensors (lidar, radar, cameras). This project is constituted of 14 french partners (Renault, Valéo, INRETS/LCPC/LIVIC, INRIA (emotion, icare, imara), CEA List, Université Paris Sud, CNRS/heudiasyc, LASMEA, Armines (CNN, CAOR)).

6.7. 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.

6.8. 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, busses 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. Other Grants and Activities

7.1. European projects

7.1.1. 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 will investigate and apply Bayesian models and approaches in order to develop artificial cognitive systems that can carry out complex tasks in real world environments. We will take inspiration from the brains of mammals including humans and apply our findings to the developments of cognitive systems. The conducted research shall result in a consistent Bayesian framework offering enhanced tools for probabilistic reasoning in complex real world situations. The performance will be 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” [36] which regroups 12 different PhD theses defended within the BIBA and BACS European projects. See: [37], [39], [41], [43], [46], [47], [48], [52], [50].

7.2. International projects

7.2.1. ICT-Asia “FACT” and ICT-Asia “City Home”

[October 2005-December 2007] and [november 2008 - December 2011]
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 planned 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: [51]
- 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: [34], [26]

7.3.2. Collaboration with LPPA-Collège de France

- Subject 1: Bayesian models of perception of shape by movment. Common PhD thesis and commun publication: [4]
- Subject 2: Bayesian models of superior colliculus, see 5.4.5 and commun publications: [5] [33].

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 (MOV INRIA+NTV, MOV INRIA + NUS, PICS CNRS including the LPPA (College de France, Alain Berthoz), ACT-Asia FACT) 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 codirected PhD students. Brice Rebsamen will defend his phD Thesis in Singapore in January 2009; Christopher Meng Tay will defend his phD in Grenoble in april 2009.

7.4.2. Collaboration with Japan, Korea, China

see the description of the ICT-ASIA “Fact” and “City Home” projects above.

7.4.3. Collaboration with Spain

Partner: UPC Barcelona. Subject: visual dynamic obstacle detection. Collaborative work, visiting scientist.

7.4.4. Collaboration with Mexico

The thematic network "Image et Robotique" has been implemented from the French-Mexican symposium in C omputer 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 and Dr Ruben Garcia Raminez spent a few months a e-Motion in 2008).

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: [18], [29]

7.4.6. Collaboration with Brasil

e-motion collaborate with 2 universities: University of Brasilia. subject: Bayesian Robot programming. Collaborative work an commun publication: A journal paper under review.

Catholic University of Brasilia. Subject: Corruption detection. Collaborative work, visiting professor.

7.4.7. Collaboration with Switzerland

Subject 1: Bayesian model of mentalizing. Partner: Les hôpitaux universitaires des Genève. Collaborative work and commun publication: [7] Subject 2: Bayesian robotics. Partner: ETH Zurich. Collaborative work and commun publications on bayesian Robotics.

8. Dissemination

8.1. Organization of scientific events

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

- C. Laugier and J.M. Ahuactzin participated to the organizing committee of the 2008 summer school on “Image and Robotics” (SSIR) at the University Blaise Pascal, Clermont-Ferrant (July 2008).
- 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 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.
- C. Laugier has 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) and in the scope of the ICT-Asia network FACT (Seoul 2005, Tokyo 2006, Shanghai 2007). He will also organize a workshop at IEEE ICRA’09.
- A Martinelli (since 2007) and C. Laugier (since 1999) are members of the permanent organization committee of the Field Service Robotics
- Pierre Bessière organized in january 2008 the “Bayesian Cognition” international winter school which gathered 80 students for a week in Chamonix.

8.2. Books and special issues publications

- Book “Autonomous navigation in dynamic environments”, Edited by C. Laugier and R. Chatila. Springer Tracts in Advanced Robotics (STAR) volume 35, Springer-Verlag, July 2007.
- 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.
- Book “Field and Service Robotics. Results of the 6th International Conferenceâ, Edited by C. Laugier and R. Siegwart. Springer Tracts in Advanced Robotics (STAR) volume 42, Springer-Verlag, February 2008.
- Special issue of the International Journal of Vehicle Autonomous Systems (IJVAS) âAdvances in Autonomous Vehicles Technologies for Urban Environmentâ, Guest Edited by D. Wang, S.Sam Ge, and C. Laugier. Volume 6, 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 Robotics Research (IJRR) “Field and Service Robotics”, Guest Edited by C. Laugier, A. Martinelli, C. Pradalier, and R. Siegwart. Publication scheduled for the first trimester of 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. Publication scheduled for the first trimester of 2009.

8.3. Visiting scentists in abroad laboratories

Some members of *e-Motion* spent some time in foreign laboratories.

- A Martinelli spent a couple of months at the Minnesota State University to work with Prof Stergios Roumeliotis on cooperative localization. During this stay, he also gave a seminar on his recent research activity.
- T Fraichard spent a year at the Autonomous Systems Lab., Swiss Federal Institute of Technology, Zurich (CH)

8.4. Academic Teachings

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

- Lecture “Robotics: Grand challenges, Research issues, and future Application domains” (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, P. Bessière.*
- Lecture “Robotics and Computer Vision”: International Master MOSIG (M1), INPG, Grenoble, (FR). *Teachers: C. Laugier, O. Aycard, E. Boyer, E. Arnaud.*
- Lecture “Basic tools and models for Robotics” (every year): Cnam Grenoble. *Teachers: C. Laugier and J. Troccaz.*
- Motion Planning course, Europe-France Summer School on Image and Robotics (SSIR): Clermont-Ferrand (FR), *June 2008. Teacher: Th. Fraichard.*
- 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)
- “Bayesian models of sensory-motor systems” course, Bayesian Cognition winter school. Teacher: P. Bessière
- “Bayesian models of sensory-motor systems” course, Summer School on Image and Robotics (2008). Teacher: P. Bessière

8.5. 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 commitee.
- Christian Laugier is a scientific consultant of the Probayes compagny in the scope of an INRIA/Probayes agreement and with the authorization of the French Deontology commitee (since oct 2008).

8.6. 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). He is also invited associate editor of the journal IEEE Transactions on Intelligent Transportation Systems.
- A Martinelli is a member of the editorial board of the IEEE Transaction on Robotics (since November 2007)
- C. Laugier and A. Martinelli are guest editors for a special issue on IJRR journal (to be published in 2008/2009)
- C. Laugier and A. Martinelli are guest editors for a special issue on JFR journal (published in 2008)
- Th. Fraichard is a regular member of the programme committees of the ICRA and IROS conferences. He is also Associate Editor for the ICRA 2009 edition. In 2008, he was also a member of the following programme committee: Int. Symp. on Distributed Autonomous Robotic Systems (DARS), Tsukuba (JP), *Nov. 2008*.
- O. Aycard is member of the programme committees of the ITSC'2008 conference.
- A. Spalanzani is part of the editorial commitee 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)
- P. Bessière reviews regularly in the IEEE Transactions on Evolutionary Computation and Autonomous Robots journals.

8.7. Invited talks

- C. Laugier "Bayesian approaches for autonomous mobile robots", Tokyo University, december 2007.

- C Laugier “Perception-based navigation for autonomous vehicles in open and dynamic environments”, Co-mobility Workshop, january 2008.
- C Laugier is invited to be Keynote speaker at the FSR’09 conference (The International Conference 2009 on Field and Service Robotics, Cambridge).
- Th. Fraichard “Motion Safety in Dynamic Environments”, Swiss Polytechnic Federal Inst., Zurich (CH), Jan. 2008.
- Th. Fraichard “Dynamic Environments and Safe Motions”, University of Judea and Samaria, Ariel (IL), Dec 07.
- Th. Fraichard “Safely Navigating in dynamic environments”, Simon Fraser University, Vancouver (CA), Dec 07.
- P. Bessière was invited in japan for the conference ISRR 2007. The title of the talk was: "Bayesian Programming: life science modeling and robotics applications" [57]

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