INRIA, Evaluation of Theme Robotique

Project-team e-Motion

March 2009

Project-team title : e-Motion

Scientific leader : Christian Laugier

Research center : INRIA Grenoble Rhône-Alpes

Common project-team with : Laboratoire d'Informatique de Grenoble (LIG)

1 Personnel

Personnel (October 2004)

	Misc.	INRIA	CNRS	University	**Total**
DR (1) / Professors		1	1		**2**
CR (2) / Assistant Professors		2	1	2	**5**
Permanent Engineers (3)					**0**
Temporary Engineers (4)		3			**3**
PhD Students	4	1		3	**8**
Post-Doc.		1			**1**
Total	**4**	**8**	**2**	**5**	**19**
External Collaborators					**0**
Visitors (> 1 month)					**0**

(1) "Senior Research Scientist (Directeur de Recherche)"
(2) "Junior Research Scientist (Chargé de Recherche)"
(3) "Civil servant (CNRS, INRIA, ...)"
(4) "Associated with a contract (Ingénieur Expert or Ingénieur Associé)"

Personnel (March 2009)

	Misc.	INRIA	CNRS	University	**Total**
DR / Professors		1	1		**2**
CR / Assistant Professor		2		2	**4**
Permanent Engineer			0.5		**0.5**
Temporary Engineer		4			**4**
PhD Students	4	6		1	**11**
Post-Doc.		1			**1**
Total	**4**	**14**	**1.5**	**3**	**22.5**
External Collaborators	4		1		**5**
Visitors (> 1 month)	2	2			**4**

Changes in staff

Number of scientific staff that joined or left the project-team during the last four years period or since the project creation. TBR.

DR / Professors CR / Assistant Professors	Misc.	INRIA	CNRS	University	total
Arrival		1CR			1
Leaving		1CR	1DR		2

Comments : *Emmanuel Mazer (DR2 CNRS) is now PDG of our start-up "Probayes", and Sepanta Sekhavat (CR1 INRIA) is now working in Iran in a private company.*

Current composition of the project-team (March 2009):

- Christian Laugier, DR1 INRIA
- Pierre Bessiere, DR2 CNRS
- Thierry Fraichard, CR1 INRIA
- Agostino Martinelli, CR1 INRIA
- Olivier Aycard, Associate Professor UJF
- Anne Spalanzani, Associate Professor UPMF
- Amaury Nègre, IR2 CNRS
- Jean-Marc Bollon, Temporary Engineer (BACS IST project)
- Christophe Mangeat, Temporary Engineer (LOVe ANR project)
- Tej Dallej, Temporary Engineer (GRAAL Imaginove/FUI project)
- Igor Paromtchik, specialist Engineer (ArosDyn ADT INRIA Project)
- Manuel Yguel, PhD student (CIFRE fellowship)
- Christopher Tay Meng Keat, PhD student (INRIA fellowship)
- Chiara Fulgenzi, PhD student (Marie Curie fellowship)
- Trung-Dung Vu, PhD student (European Profusion project fellowship)
- Thiago Bellardi, PhD student (European Bacs project fellowship)
- Estelle Gilet, PhD student (European Bacs project fellowship)
- Luis Martinez-Gomez, PhD student (INRIA fellowship)
- Vivien Delsart, PhD student (DGA fellowship)
- Qadeer Baig, PhD student (Pakistan fellowship + INRIA)
- Yong Mao, PostDoc (Denso Contract)
- Guillem Alenya Ribas, Visitor (UPC Barcelona)
- Frank Moosmann, Visitor (Karlsruhe University)

Current position of former project-team members (including PhD students) during the 2004-March 2009 period:

Provide a list of former project-team members including name, current position, name and location of the employer. TBR.

- Emmanuel Mazer (DR2 CNRS), PDG of Probayes company
- Sepanta Sekhavat (CR1 INRIA), currently working in a private company in Tehran (Iran)
- Kenneth Sundaraj (PhD Thesis 2004), Associate Professor, Northern Malaysia University
- Cedric Pradalier (PhD Thesis 2004), Research Associate, Autonomous System Laboratory, ETH Zurich
- Miriam Amacviza Ruiz (PhD Thesis 2005), Temporary Engineer at Probayes in 2008, Now in Puebla (Mexico) since January 2009
- Carla Koike (PhD Thesis 2005), Associate Professor, University of Brasilia
- Francis Colas (PhD Thesis 2006), Postdoc, Autonomous System Laboratory, ETH Zurich
- Pierre Dangauthier (PhD Thesis 2007), Engineer at Barclays Wealth, London
- Julien Burlet (PhD Thesis 2007), Engineer in a private company, London
- Alejandro Dizan Vasquez (PhD Thesis 2007),Postdoc, Autonomous System Laboratory, ETH Zurich
- Ronan LeHy (PhD Thesis 2007), Engineer at Probayes
- Stéphane Petti (PhD Thesis 2007, also in IMARA EPI), Engineer in a private company, Brussels
- Christophe Braillon (PhD Thesis 2007), INRIA Research Engineer, SED INRIA Grenoble Rhône-Alpes
- Rodrigo Benenson (PhD Thesis 2008, common with IMARA EPI), Postdoc at Ecole des Mines de Paris
- Amaury Negre (PhD Thesis March 2009), CNRS Research Engineer, LIG Laboratory
- Brice Rebsamen (PhD Thesis February 2009), Research Associate at NUS (Singapore)

Last INRIA enlistments

- Agostino Martinelli (previously Associate Researcher at EPFL), 2006, CR1.

Other comments :

Since January 2009, the LIG Laboratory has provided us with 0.5 CNRS Research Engineer (Amaury Negre) for the development and the maintainance of our experimental platform.

2 Work progress

2.1 Keywords

Bayesian Programming, Reasoning under Uncertainty, Dynamic World constraints, Robotics, Autonomous Navigation, Artificial Perception, Motion Planning, Learning, Modeling biological Sensory-Motor Systems.

2.2 Context and overall goal of the project

2.2.1 Motivation and overall challenge

The main general challenge we are addressing is to develop new models and approaches for contributing to achieve an old dream of Robotics researchers : *"Robots sharing the Human living space"*. We have first proposed this ambitious challenge during a brainstorming meeting organized by the EC in preparation of the FET (Future Emerging Technology) CFP "Beyond Robotics". From the scientific point of view, this challenge leads to deeply revisit some of the traditional approaches which are not fully adapted to the processing of *Uncertainty*, *Complexity*, *Dynamicity* and *Interaction* constraints coming from real world applications involving human beings.

More precisely, the project-team *e-Motion* aims at developing new models and algorithms which should be required for building *"intelligent artificial systems"* 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 human beings.* 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).

2.2.2 Approach and research themes

In order to try to reach the previous objective, we combine the respective advantages of Geometric & Tological models with Probablistic models[1]. In order to take into account the Human factor, we are also working in cooperation with neurophysiologists for studying and trying to models sensory-motor systems using Bayesian approaches. Three strongly correlated fundamental research themes are studied under the previous point of views :

- *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 fundamental questions : How to efficiently model the various relevant aspects of the real environment ? 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

[1] see http://emotion.inrialpes.fr

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 ?

- *Bayesian models for Learning, Decision, and Sensory-motor systems.* 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 extend our Bayesian programming paradigm, while collaborating with neurophysiologists on some selected topics such as the study of human navigation mechanisms or the modeling of biological sensory-motor loops. The main questions we are addressing are the followings : How to model sensory-motor systems and the related behaviors ? How to take safe action decisions under uncertainty ? What kind of models and computational tools are required for implementing the related Bayesian inference paradigms ?

2.2.3 Scientific positioning

Our objectives and approach is both original and consistent with the approach proposed at the same time by Sebastian Thrun from Stanford University (where "Probabilistic Robotics" is akey concept). On one hand, we have been among the pioneers (in particular Pierre Bessiere) in the development of the powerful concept of *"Bayesian Programming"*. On the other hand, we have pioneered methodologies for dealing with *safety issues* in Motion Planning for dynamic environments (in particular with our original concept of "Partial Motion Planning" and of "Inevitable Collision State"). The idea of combining this new approach based on analytical models (geometry, topology, kinematics, dynamics) with Bayesian Programming tools specially designed for reasoning about uncertainty, is clearly the main originality of *e-Motion*; an other originality comes from our objective to explicitly take into account the Human factor by working in cooperation with neurophysiologists for studying and trying to model living systems.

Such a scientific approach is now becoming more and more popular in the Robotics community. Several facts might be considered as evidences of the success of this approach :

- Our results on Bayesian Programming tools have given rise to the creation of our Start-up "Probayes" who is now growing quite well, and who is still strongly cooperating with *e-Motion*.

- We have obtained and conducted important National and European research contracts, e.g. the European projects *BIBA* (Bayesian Inference and Brain Artefacts) coordinated by our team until 2005, the European project *BACS* (Bayesian Approach to Cognitive Systems) launched as a follow up of *BIBA*, and the European projects *PreVent* and *Intersafe 2* respectively coordinated by Daimler Chrisler and Ibeo (where we are focusing on sensor fusion for Advanced Driving Assistance Systems).

- Our scientific results on Bayesian Perception (including some patented results) has also lead us to the signing of important R&D contracts with large companies in the field of automotive industry (i.e. TOYOTA and DENSO). All these industrial contracts are conducted in cooperation with our start-up company *Probayes*.

- From the academic point of view, we have organized since 2005 several workshops on these topics in the scope of the major international conferences IEEE ICRA and IEEE/RSJ IROS. These workshops, dealing about "safe navigation and decision in dynamic environments", have involved well known researchers of the domain (e.g. Sebastian Thrun, Roland Siegwart, Wolfram Burgard, Alberto Broggi, Raja Chatila, Henrik Christensen ...) and have gathered together an increasing number of participants (e.g. about 70 persons in Beijing in 2006, and about 100 persons in Nice in 2008). As a result, we have published two books (in Springer STAR) and two special issues of scientific journal.

2.2.4 Main application domains

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.

- *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*[2] 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).

- *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.

- *Potential spin-offs of Bayesian Programming in some other application domains.* The software technologies we are developing in cooperation with our start-up *Probayes* have clearly 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. These new applications are mainly addressed by our start-up *Probayes* who is commercializing products based on Bayesian programming).

2.3 Objectives for the evaluation period

2.3.1 Objectives given at the creation of the project-team (copy)

Obj 1: Multimodal and incremental modelling of space and motion :

- *SLAM in a dynamic environments.* The objective is to be able to build an "evolutive map" taking into account both world changes and temporary obstacles; we will try

[2] Advanced Driver Assistance Systems

to use several sensing modalities (including vision) for processing natural landmarks and for improving the robusteness of the system. A special emphasis will be put on uncertainty processing and self diagnosis (using bayesian programming).

- *Bayesian maps for sensory-motor based navigation.* Our initial theoretical work will be extended and experimentally compared to some biological theories (in cooperation with A. Berthoz laboratory); in a second step, we will try to apply this approach to one of our mobile robots equipped with several sensing modalities.

- *Future motion prediction for potential obstacles.* The objective is to integrate various knowledges in the prediction process (e.g. kinematics constaints) and to try to extend the approach to less structured scenes (e.g. in the INRIA car park).

- *Interpretation of dynamic scenes using bayesian data fusion.* This is an important topic for the development of ADAS systems. Three main research directions will be followed for extending our current approach: dealing with multi-sensor and multi-target scenarios, methods for obtaining real-time responses in large environments, and integration of a priori knowledges within the prediction phase.

Obj 2: Motion planning for the physical world :

- *Safe navigation using bayesian programming.* The objective is to be able to correctly combine a bayesian obstacle avoidance system (for a reactive tracking of planned trajectories) and a robust controller for the Cycab (e.g. based on flat outputs). Both data fusion problems and control problems will be addressed.

- *Iterative trajectory planning (ITP).* We will both develop the required theoretical material and the related algorithmic problems. As for the safety issue (i.e. avoiding critical situations), we will explore more deeply the two solutions respectively based on NLVO (non-linear velocity obstacles) and on the concept of "inevitable collision states". We will also explore the problem of the coupling of the ITP layer with the control layer of the system.

Obj 3: Probabilistic inference for decision :

- *Models and tools for bayesian inference.* We will continue to develop new algotithms for the bayesian inference (both at the symbolic and numerical levels), in order to find a good compromise between computational time and memory size. We will also work on the problem of the estimation of variable dependencies from a set of experimental data.

- *Bayesian robot programming.* We will continue the current work on three basic sub-problems : safe navigation along sensori-motor trajectories, consistent information selection in large sets of sensory data, and fusion/combination of reactive behaviors inspired from biology. The last point will be studied in collaboration with the neurophysiologists involved in the BIBA project.

- *Learning bayesian behaviors.* The main objective is to study how to learn adaptive behaviors from time-dependent experimental data. In a medium term, this work will be done in scope of virtual worlds (e.g. video games), where such experimental data (i.e. virtual perception, sequences of controls, failures ...) are more easy to obtain and to process. This work will be done in cooperation with the *Evasion* and *Siames* project-teams in the scope of a Robea project.

2.3.2 Evolution of the objectives during the evaluation period

All the proposed objectives have mainly been addressed during the evaluation period, sometime with a slightly different but more successful approach. The main results are briefly described in the next section. It should be noticed that for consistency and clarity reasons, we have slightly modified the structure and the titles of the three main objectives of e-Motion.

Only slight local deviations of the objectives have been applied during the evaluation period. These deviations concern the four following topics which have partially been addressed or slightly modified (mainly for consistency and/or work-force reasons) :

- *Bayesian maps for sensory-motor based navigation.* This topic has been addressed in a slightly different way in collaboration with Alain Berthoz from LPPA Collège de France. Basically, we have applied this paradigm for studying human navigation by comparing simulation results of our models with psycho-physical experiments in a virtual reality environment. This work has mainly been conducted in *e-Motion* by Pierre Bessiere and Julien Diard (who is now a CNRS Research Associate in the Laboratory of Psychology and Neurocognition in Grenoble, and an external collaborator for *e-Motion*).

- *Safe navigation using bayesian programming.* This topic has partially been addressed, since the main researcher in charge of this work (Sepanta Sekhavat) has left at the beginning of the evaluation period. However, it should be noticed that the other related points has been expended more deeply than previously expected (see results in the next section).

- *Learning bayesian behaviors.* The work on this topic has successfully been addressed during the evaluation period (cf. PhD thesis of Ronan Le Hy), and the results which have been obtained have recently given rise to a new R&D contract GRAAL involving our start-up *Probayes* and two Video Games and Robotic companies. However, the planned collaboration with the Project-Teams *Evasion* and *Siames* on the related "animation" topic has been less successful than previously expected.

- *Models and tools for Bayesian Inference.* The work on this topic has successfully been performed during the evaluation period in tight collaboration with *Probayes*. Most of the results have been integrated into the *ProBT* library of *Probayes*. We are progressively stopping to work on this topic.

2.4 Executive summary (Obj 1) : "Dynamic world perception and understanding"

2.4.1 Personnel

Permanent researchers and External collaborators: Olivier Aycard; Christian Laugier; Anne Spalanzani; Agostino Martinelli; Thierry Fraichard; Amaury Negre (CNRS Engineer since 2009); Kamel Mekhnacha (Engineer at Probayes).
Ph.D students, Posdocs, and Temporary engineers: Julien Burlet (until 2007); Dizan Vasquez (until 2007); Christophe Braillon (until 2007); Amaury Negre (until 2009); Manuel Yguel; Christopher Tay Meng Keat; Trung-Dung Vu; Thiago Bellardi; Qadeer Baig; Yong Mao (Postdoc); Christophe Mangeat (Temporary Engineer since 2008); Igor Paromtchik (Specialist Engineer since 2008).

2.4.2 Project-team positioning

Perceiving and understanding the surrounding physical world in a reliable way is a major issue for the development of autonomous robots. The main difficulty in our case, comes from the fact that we are dealing with open and highly dynamic environments (i.e. involving stationary obstacles, moving entities having various unknown dynamic behaviors, complex environments, and sensing uncertainty).

A first issue concerns the *Robust Detection and Tracking* of surrounding objects using various sensing modalities. A considerable research material already exists on both the SLAM (Simultaneous Localization and Mapping) and DATMO (Detection and Tracking of Moving Objects) problems. However, for highly dynamic outdoor environments like crowded urban streets, there still remains many open questions closely related to robustness and efficiency issues (in particular for avoiding errors coming from data association and occlusion problems). Our objective is to develop robust Bayesian detectors and trackers for solving this problem.

The second issue concerns the *Localization and Mapping problem*. This is traditional research issue which has already been intensively addressed by the Robotics Community. Indeed, this issue is fundamental to achieve good performance and robustness in navigation systems. In this general framework, we are interested in the development of robust models for solving three important issues related to the open and dynamic environments context: Sensor self-calibration, Multi-modality localization, Efficient 3D mapping.

The third issue concerns the *World change prediction and the Risk assessment*. This is a new and challenging research topic. Few contributions currently exist in the literature. The main related work concerns the observation and the prediction of human activities using vision data (e.g. on-going work at CMU). Addressing this topic is essential for being able to achieve safe navigation in open and dynamic environments. Indeed, taking safe navigation decision in such environments require to continuously estimate the situation, while evaluating at any time the danger (i.e. probability of future collisions) by predicting the most likely evolution of the environment (this is the typical activity of a human drivers). Our objective is to develop such models.

2.4.3 Scientific achievements

Dynamic world perception. Two complementary approaches have been developed for achieving a robust perception of the dynamic environment:

- *Vision based obstacles detectors.* The basic idea is to fuse several sensing modalities for achieving a more robust and accurate detection of the potential obstacles. The approach consists in coupling stereo-vision methods and monocular camera's methods using optical flow and scale-space representation to extract from images moving and static obstacles. When the ego-motion of the camera is known, we compute the theoretical optical flow field (using odometry) in order to detect pixels that don't match this model [11]. When the ego-motion cannot be estimated, we use a detector of "growing objects"; this detector can extract and track particular region of interest called Scale Invariant Ridge Segments (SIRS) in an image and is able to estimate the Time-To-Contact of the detected objects (this method is based on a human reflex called "looming") [137] [18]. In order to improve the robustness and to take into account the advantage and weakness of each method, the resulting data are fused and filtered using the Bayesian Occupancy Filter framework [84]. More recently, we have also started to experiment a new promising approach based on the use of statistical classifiers and Self Organizing Networks (SON) [95].

- *Object detection and tracking.* In order to overcome the main drawbacks of the traditional feature-based methods, we have developed a new approach combining probabilistic grids and Bayesian filtering techniques. In this approach, we have simultaneously developed methods based on the traditional Occupancy Grid model (*OG*), and methods based on our new concept of *Bayesian Occupancy Filter (BOF)* consisting in reasoning about both position and velocity probabilities[3] [67, 34]. In both *OG* and *BOF* models, detection & tracking problems have been addressed by combining dedicated Bayesian filtering and data association methods involving probabilistic sensor and dynamic models. Several theoretical and practical results have been obtained: Localization and mapping using scan matching & grid correlation [169]; Fast clustering & tracking using the *BOF* paradigm for integrating in a single process the detection and tracking functions [133, 132]; Multiple-models for robust multi-object tracking [12]; Data-driven Markov chain Monte Carlo (DDMCMC) tracking [170]. The current work aims at improving the robustness of the approach by pushing further our idea to combine the detection and tracking functions in a single process.

Localization and mapping. Three complementary topics have been addressed during the evaluation period:

- *Sensor self-calibration.* A satisfying convergence of localization and mapping methods (which are usually based on statistical methods) can only be achieved if no systematic error component exists in the sensor data. Then, removing this systematic component in real applications is necessary. We claim that this can be done using a calibration strategy having the capability of operating in a completely unknown environment (by only using some simple data coming from the robot sensors). An original solution for simultaneously performing the calibration of proprioceptive and exteroceptive sensor data has been developed for that purpose [155, 125, 7, 195, 129]. The results obtained using this method are impressive in terms of precision and robustness.

- *Feature based localization and mapping.* The main contribution concerns a new hybrid approach to perform the estimation. The novelty relies on a combination of a linear estimator (basically the information filter) and a non linear estimator. We already adopted this new concept in a relative map approach to SLAM [127, 123]. In this case, the information filter estimates relative quantities between the features which are invariant with respect to shift and rotation; the non linear estimator was adopted to remove geometrical dependencies in the estimated state. We are now extending these approaches in order to also use proprioceptive data which are basically discarded in a relative approach.

- *Efficient grid based 3D mapping.* 3D models are used for robot localization and navigation. In our general framework, we are using Probabilistic Grid Maps. Our objective is to construct efficient and concise models (i.e. to drastically reduce the complexity of the world models). We have developed several complemtary approaches for solving this problem: Using a GPU for efficiently constructing 2D occupancy grids [72]; Contructing and updating 3D occupancy grid using wavelets (saving in this way about 90% of the memory) [173]; Constructing multi-scale maps based on ellipsoids and coupled with robust registration methods (on-going work done in the scope of

[3] The *Bayesian Occupancy Filter (BOF)* has been patented and transfered to the industry (see section 3.3)

the PhD thesis of Manuel Yguel, in cooperation with Radu Horaud (Perception) and Bernard Mourrain (Galaad) [209]).

Prediction and Danger assessment. Very interesting results have been obtained on this challenging topic. The results about the "risk assessment" issue have been obtained in the scope of our cooperation with Toyota.

- *World change prediction.* The problem is to reason about the future behavior of the moving entities observed in a dynamic scene. Since this future behavior is unknown, one has to use prior knowledge and current & past observations to make predictions. The few techniques proposed in the literature are mainly limited to short-term predictions and to the use of a previously learned motion pattern basis. Our approach is to use a "continuous learn & predict" paradigm, based on the new concept of *Growing Hiden Markov Model (GHMM)* [71, 70, 22]. Real data have been used for validating the approach and for comparing the results to some other methods.

- *Risk assessment.* Making an assessment of the potential future collision in a dynamic environments is a useful tool for both safe navigation systems or advanced driver assistance systems. Very few material exists in the literarture on this topic. We have started to develop an approach based on the concept of *Gaussian Process (GP)*, where the moving objects of the environment are represented by a mixture of GP (each GP representing a particular motion pattern); then, the risk assessment is achieved by marginalizing the gaussian distribution given a set of observations [159]. This work is done in the scope of the PhD thesis of Christopher Tay Meng Keat. We should stress that some very interesting results have been obtained in the scope of the Toyota contract. We have also started to study an other application of the risk assessment approach, consisting in coupling it with a probabilistic Motion Planner [112]

2.4.4 Collaborations

Collaborations with other INRIA project-teams:

- Imara, Paris Rocquencourt; Autonomous navigation; Collaboration within Puvame & LoVe & Cybercars & HaveIt & Intersafe2.

- Lagadic, Rennes Bretagne Atlantique ; Visual SLAM ; Collaboration within H-VIS.

- Perception, Grenoble Rhône-Alpes ; Calibration, localization, and reconstruction; Collaboration within ArosDyn.

- Prima, Grenoble Rhône-Alpes ; Detection and tracking of moving objects; Co-directed PhD student and collaboration within ArosDyn.

- Galaad (Bernard Mourrain), Sophia-Antipolis ; Mathematical models for registration algorithms; No particular support for the collaboration.

- Ezio Malis (from Arobas), Sophia-Antipolis; Visual tracking; Collaboration within ArosDyn.

Collaborations with French research groups outside INRIA:

- Groupe Robotique et Intelligence Artificielle (RIA), CNRS-LAAS, Toulouse; Humanoid robotics; Collaboration within H-VIS.
- LASMEA Clermont Ferrand, Vision based navigation; Collaboration within Mobivip & LoVe & FACT & CityHome.
- INRETS Lyon, HMI for driving assistance system; Collaboration within Puvame.
- INRETS Livic, Vision based navigation; Collaboration within LoVe.

Collaboration with Foreign research groups:

- Autonomous Systems Lab., Swiss Federal Inst. of Technology (ETH), Zürich (CH); Safe automated driving, 3D mapping, Localization, and Prediction; Collaboration within BIBA & BACS & Sfly.
- NTU Singapore, SKKU University Seoul, SJTU Shanghai, Tokyo University; Intelligent vehicles; Collaboration within FACT & CityHome.
- NUS Singapore; Brain controlled wheelchair; Collaboration within PICS CNRS (Co-directed PhD and common publications).
- University of Minneapolis (Prof Stergios Roumeliotis); Formal work on multi-robot localization; Visits and collaboration within sFly.
- University of Rome Tor Vergata; Localization and mapping; Visits and commun publication (ICRA 2007).
- University of L'aquila; Visits, lectures, student exchanges and common publication.

2.4.5 External support

- European project **BACS**, "Bayesian Approach to Cognitive Systems", *[2006-2010]*.
- European project **Cybercars 2**, "Close Communications for Cooperation between Cybercars" *[2006-2008]*.
- European project **PreVent**, "Preventive and Active Safety Applications" *[2004-2008]*.
- European project **sFLY**, "Swarm of micro flying robots" *[2009-2011]*.
- ICT-Asia **FACT** and **CityHome**, "Intelligent Transportation Systems" *[2005-2011]*.
- Predit **Puvame**, "Protection of weak traffic participants" *[2003-2006]*.
- Predit-ANR **LoVe**, "Logiciel d'observation de vulnérables" *[2005-2009]*.
- Robea **ParkNav**, "Interpretation of Complex Dynamic Scenes and Reactive Motion Planning" *[2002-2005]*.
- Industrial contract **Toyota**, "Driving assistance system" *[2005-2010]*.
- Industrial contract **Denso**, "Robust traffic situation assessment" *[2006-2008]*.

2.4.6 Self assessment

Perceiving and understanding the surrounding physical world in a reliable way is a major issue for the development of autonomous robots. During the evaluation period, we have successfully addressed three complementary aspects of this problem: Dynamic world perception, Localization and mapping, Prediction & Risk assessment. Both theoretical and practical solutions have been developed and tested on several academic and industrial experimental data and platforms. The work done during the evaluation period on these three issues will be continued during the next four years; however, we will put more effort on the solving of efficiency and robustness problems.

The most promising results which have been obtained during the evaluation period are:

- *The Bayesian Occupancy Filter (BOF)* which has been patented and transfered to the industry (see section 3.3).Thanks to this result, several industrial contracts have been signed (Toyota, Denso, Hitachi). New improvements (efficiency, accuracy, memory requirement) will be studied in the next four years.
- *The multiple object tracker* which has successfully been tested on the Daimler-Chrysler experimental vehicle. Even if the experimental results were satisfying, we have started to study a new promising approach aiming at considering the detection and tracking functions as a single process; this approach should lead to improve the robustness of the tracker.
- *The 3D multi-scale mapping approach* which has been designed for representing in an efficient way complex multi-modal environmental data; the long term objective is to design hybrid maps and SLAM algorithms by coupling our feature based approach with an optimized grid based representations.
- *The Risk assessment function* which is based on the Gaussian Process paradigm; Very interesting results have been obtained in the scope of the Toyota contract. This work should be continued during the next four years, in collaboration with Toyota.

2.5 Executive summary (Obj 2) : "Motion Planning and Autonomous Navigation in the Real World"

2.5.1 Personnel

Permanent researchers: Thierry Fraichard; Christian Laugier; Anne Spalanzani.
Ph.D students: Stéphane Petti (until 2007); Rodrigo Benenson (until 2008); Vivien Delsart; Luis Martinez-Gomez; Chiara Fulgenzi.

2.5.2 Project-team positioning

We are addressing the challenging problem of motion planning and/or autonomous navigation in *open* and *highly dynamic* environments (such as the road network) from both a theoretical and practical perspective (in cooperation with the EPI Imara through the Cybercar initiative for the latter aspect).

Not that many are the research groups worldwide that address this problem. In France: LASMEA in Clermont-Ferrand and its PAVIN platform; in Europe, ETH Zurich (Roland Siegwart's group) and University of Freiburg (Wolfram Burgard's group) with the

SmartTer project; In the US, Stanford and Carnegie Mellon University may be the most renowned ones (in the wake of their success in the 2007 DARPA Urban Challenge).

In spite of its success in the media, the number of incidents/accidents that occurred during the 2007 DARPA Urban Challenge has demonstrated that motion safety remains an issue. In this respect, e-Motion's work on the two complementary concept of *Inevitable Collision States* and *Safe Navigation under Situation Assessment & Prediction* is at the forefront of the research in this domain.

2.5.3 Scientific achievements

When it comes to motion in dynamic environments, the primary achievements obtained by *e-Motion* have been to emphasize that a number of safety criteria **must** be considered when a robotic system wants to navigate in a dynamic environment [108]. As straightforward as these criteria may appear, they so far have been strangely ignored by the robotics community.

Inevitable Collision States. Seminal in the definition of these motion safety criteria has been the novel concept of **Inevitable Collision States** (ICS) introduced in [39]. The theoretical study of this concept has led to the definition of `ICS-Check` [130] and then `ICS-Avoid` [131], the first collision avoidance scheme for which given levels of motion safety can be **guaranteed** (in contrast to all previous collision avoidance schemes).

PMP framework. The integration of `ICS-Check` within our Partial Motion Planning (PMP) framework (introduced in 2001) led to the implementation and experimental validation of a safe navigation scheme [145, 76]. A navigation architecture sharing the same philosophy is currently being implemented and tested on the SmartTer vehicle of ETH Zurich [122].

Besides, we have proposed `Trajectory Deformation` as a way to to address the uncertainty and convergence[4] issues intrinsic to open dynamic environment. A trajectory deformation scheme name `Teddy` has been designed and successfully tested in simulation [100].

Safe goal-oriented navigation. Finally, we have started to integrate the PMP framework with our *Bayesian Estimation & Prediction paradigm* (see section 2.4). This approach aims at explicitly taking into account the *Uncertainty and Dynamicity characteristics* of the real world, when making goal-oriented safe navigation decisions [111] [112]. This work is done in the scope of the PhD thesis of Chiara Fulgenzi (to be defended in May 2009) and to the EU *Visitor* project.

2.5.4 Collaborations

Collaborations with other INRIA project-teams:

- Imara, Paris Rocquencourt; Autonomous navigation; Collaboration within Cybercars & HaveIt.
- Lagadic, Rennes Bretagne Atlantique ; Detection and tracking of moving objects; Collaboration within ParkNav.

[4]The guarantee of eventually reaching the goal.

- Perception, Grenoble Rhône-Alpes ; Detection and tracking of moving objects; Collaboration within ParkNav.
- Prima, Grenoble Rhône-Alpes ; Detection and tracking of moving objects; Collaboration within ParkNav.

Collaborations with French research groups outside INRIA:

- Groupe Robotique et Intelligence Artificielle (RIA), CNRS-LAAS, Toulouse; Trajectory deformation; Collaboration within Parknav; One joint publication.
- DGA Paris, Groupe Véhicules Terrestres; DGA PhD Scholarship in the scope of the TAROT project; Safe trajectory generation under dynamic constraints.

Collaboration with Foreign research groups:

- Autonomous Systems Lab., Swiss Federal Inst. of Technology (ETH), Zürich (CH); Prof. Roland Siegwart; Safe automated driving.
- Centro de Sistemas Intelligentes, Tecnologico de Monterrey, Campus Monterrey (MX); Prof. Jose-Luis Gordillo; Navigation of an autonomous vehicle in a dynamic environment.
- Dept. of Mechanical Engineering and Mechatronics, Univ. of Judea and Samaria, Ariel (IL); Prof. Zvi Shiller (formerly at Univ. of California, Los Angeles); Obstacle avoidance.

2.5.5 External support

- European project **Have-It**, "Highly Automated Vehicles for Intelligent Transport", *[2008-2011]*.
- European project **BACS**, "Bayesian Approach to Cognitive Systems", *[2006-2010]*.
- European project **Cybercars 2**, "Close Communications for Cooperation between Cybercars" *[2006-2008]*.
- PAI Star **SafeMove**, "Dependable Robotic Navigation" *[2004-2005]*.
- Predit **Mobivip**, "Public Individual Vehicles for Mobility in Downtown Area" *[2003-2006]*.
- Robea **ParkNav**, "Interpretation of Complex Dynamic Scenes and Reactive Motion Planning" *[2002-2005]*.
- French-Mexican project **NavDyn**, "Navigation of an Autonomous Vehicle in a Dynamic Environment" *[2002-2004]*.

2.5.6 Self assessment

Inevitable Collision States (ICS) is a fundamental concept . It has helped to better understand motion safety in dynamic environments. It has also revealed the intrinsic complexity of the problem at hand and the difficulty of ever defining a navigation scheme with full motion safety. Lesser motion safety is in order here, especially in open environments.

So far, we have considered ICS based upon a deterministic model of the future. This is hardly compatible with the uncertain environment assumption; it is therefore important to further explore the ICS concept and to shift to a *probabilistic representation.*

As heuristic in nature as it is, Trajectory Deformation is a promising alternative navigation scheme that remains to be experimentally validated.

Partial Motion Planning (PMP) remains a core component of a navigation architecture[5]. On one hand, its coupling with ICS needs to be explored in order to determine if navigation in open and dynamic environments *with safety guarantees* can actually be achieved. On the other hand, its coupling with our *Bayesian Estimation & Prediction paradigm* for being able to really capture the open and highly dynamic nature of the environment is clearly an important issue.

There is no need to stress that if autonomous robotic systems are ever to be deployed among human beings, such guarantees will be of the utmost importance.

2.6 Executive summary for Objective 3 : "Bayesian approach to cognitive systems"

2.6.1 Personnel

Permanent researchers and External collaborators: Pierre Bessière; Christian Laugier; Anne Spalanzani; Juan-Manuel Ahuactzin (E-Motion until 2006, then Engineer at Probayes); Julien Diard (CR CNRS at LPNC).
Ph.D students and Temporary engineers: Cedric Pradalier (until 2005); Carla Maria Koike (until 2006); Francis Colas (until 2006, then external collaborator); Pierre Dangauthier (until 2007); Ronan Le Hy (until 2007); Estelle Gilet; David Partouche; Brice Rebsamen; Jean-Marc Bollon (Temporary Engineer since 2005).

2.6.2 Project-team positioning

Our work is based on the assumption that *Probability is an alternative to logic to rationally reason with incomplete and uncertain knowledge.* Probability may also be considered as an emerging cognitive paradigm for perception, action, inference, decision and learning. Consequently, such a framework can potentially be used for modeling both *Natural and Artificial Cognitive Systems.* Since several years, we have been working along four complementary research directions:

- Formalization of Bayesian probability. The result is our Bayesian Programming formalism.
- Automatization of probabilistic inference and development of industrial applications. The main result is the ProBT inference engine commercialized by our start-up *Probayes* (www.probayes.com), and several Bayesian solutions for industrial applications (see section 3.3).
- Bayesian robot programming.
- Bayesian modeling of living systems.

Thanks to the existence of *Probayes*, our research activity during the evaluation period has mainly been focused on the two last topics.

[5]See the architectures developed for the DARPA Urban Challenge.

Several communities are working on Bayesian probabilities, but a few connections exist between these communities: Mathematicians working on the theoretical aspects (mainly with an objectivist point of view); Physicists who have pioneered the subjectivist approach which is our main source of inspiration[6]; Researchers in Artificial Intelligence and in Robotics; Researchers from the Neural Information Processing Systems (NIPS) community; Researchers in Life sciences.

In order to try to launch discussions between these communities, we have organized an international workshop and a winter school on "Bayesian Cognition"[7]. Thanks to this initiative, some fruitful collaborations have been established with several life science teams (Collège de France, ENS, ICP, LPNC), and we have recently published papers in some related conferences and journals (e.g. Biological Cybernetics journal or Cosyne conference).

2.6.3 Scientific achievements

During the evaluation period, we have progressively stopped to work on the development of models and tools for Bayesian inference (since the results have been integrated into the *ProBT* library of *Probayes*). Then, we have focused our research activity on two main issues respectively related to the study of "artificial systems" (including autonomous robots) and of "living systems".

Bayesian robot programming and Bayesian learning. The main question addressed here concerns the development of efficient Bayesian artifacts for autonomous robots and artificial systems. Three main topics have been addressed during the evaluation period:

- *Bayesian approach to action selection and attention focusing.* The approach consists in constructing a probabilistic model for programming some robust reactive behaviors. A theoretical model has been developed and published (PhD thesis of Carla Koike [13]), and experimental validations have been performed using a mobile robot evolving in a dynamic environments populated by humans [1].

- *Wheelchair navigation based on learned sensory-motor skills.* This is a more prospective work. During the evaluation period, two main aspects of the problem have been addressed. The first topic concerns the modeling of sensory-motor skills and of reactive behaviors; several approaches based on Fuzzy Neural Networks and on our new concept of Growing Hidden Markov Models (GHMM, see section 2.4) have been developed [142, 202], but no really significant results have been obtained until now on real robots. The second topic concerns the human/wheelchair interaction through a Brain Computer Interface (BCI); impressive results have been obtained on this topic in collaboration with NUS Singapore (PhD thesis of Brice Rebsamen [20, 62]).

- *Bayesian learning.* Two main aspect of Bayesian learning have been addressed. The first aspect concerns the application of Bayesian learning techniques to the training of video game avatars (for both game players and game developers) (see PhD thesis of Rona Le Hy [17] [1]). This result is currently used in the scope of an industrial project (GRAAL) involving *Probayes* and a video game company. The second aspect concerns the theoretical foundations of Bayesian learning. A practical result of this work, done in collaboration with Microsoft Research, propose an efficient method for ranking chess players (see PhD thesis of Pierre Dangauthier [15] [98]).

[6] See *Probability Theory - The logic of science* by Edwin T. Jaynes, Cambridge University Press, 2003.
[7] see www.bayesian-cognition.org

Bayesian modeling of living systems. We are addressing here the following question: At the behavioral level, is there any evidence that biological systems are using probabilistic reasoning ? During the evaluation period, we have studied three main topics related to this question:

- *Perception of shape from motion.* Very often illusions or miss perceptions are explained in the psychophysics literature by some inadequate prior knowledge. The PhD thesis of Francis Colas [94, 33], which has been done in collaboration with Jacques Droulez from LPPA Collège de France, formally demonstrates that this assumption hold for the human perception of shape by the movement. This work also "explained" six traditional psychophysics experiments, by using a single probabilistic model based on two central hypotheses of the literature about the brain interpretation ("stationarity" and "rigidity" hypotheses) .
- *Bayesian models of eye movement selection with retinotopic maps.* This work consists in building a Bayesian model of the superior colliculus responsible for the control of human eyes saccades (work done in collaboration with Alain Berthoz from LPPA Collège de France). This model has been tested against data observed when accomplishing the so called "Pylyshin" pursuit task [33].
- *Bayesian modeling of sensory-motor systems: Application to handwriting.* This is an on-going work. It consists in building a Bayesian model for the reading and the writing of letters. The idea is to apply the motor theory of perception. This work is done in the scope of the PhD thesis of Estelle Gilet and of the EU BACS project. It is done in collaboration with Julien Diard from the LPNC Grenoble (Laboratoire de Psychologie et Neuro Cognition).

2.6.4 Collaborations

Collaborations with French research groups outside INRIA:

- CNRS-ICP (Institut de la Communication Parlée). Bayesian approaches to speech acquisition and evolution (Co-advised PhD, Common publications).
- CNRS-LPNC (Laboratoire de Psychologie et Neuro Cognition). Sensory motor loops (Co-advised PhD, Common publications).
- Collège de France-LPPA (Laboratoire de la Physiologie de la Perception et de l'Action). Perception of Shape from motion, Bayesian model of superior colliculus, Biochemichal probabilistic inference (Co-advised PhD, Common publications).

Collaboration with Foreign research groups:

- EPFL (Polytechnic Lausanne), Lausane (Switzerland). EEG interpretation.
- ETHZ (Polytechnic Zurich), Zurich (Switzerland). Bayesian Robot Programming (Common publications).
- HUG (Les Hopitaux de Genève), Geneva (Switzerland). EEG interpretation (Common publication).
- MPI-Tubinghen (Max Planck Institute), Tubinghen (Germany). Bayesian models of superior colliculus (Common publications).

- UnB (University of Brasilia), Brasilia (Brasil). Bayesian robot programming (Common publications).
- University of Coimbra, Coimbra (Portugal). Multimodal perception of 3D structure and Motion (Common Publication).

2.6.5 External support

- ACI complexité (2003-07)
- ROBEA "Bayesian models for Motion generation" (2002-06)
- European Project BIBA (Bayesian Inspired Brain and Artifacts, 2000-05)
- European Project BACS (Bayesian Approach to Cognitive Systems, 2005-10)
- FUI, projet GRAAL (2009-11)

2.6.6 Self assessment

The main strength of this work clearly relies on the fact that all the addressed topics are founded on the same common denominator: the Bayesian Programming formalism and modeling methodology. Due to this common mathematical background and common language, different research topics and applications can share solutions and tools. The commercialization of the related library *ProBT* by our start-up *Probayes* attests that this approach can also be used for addressing industrial applications. The strong cooperation with *Probayes* is also clearly a strength, and it should stay very active during the next four years.

From the academic point of view, we should stress that a book entitled *Probabilistic reasoning and decision making in sensory-motor system* [1] was published in 2008 by Springer, and that very interesting results have also been obtained in collaboration with researchers from Life science.

The main weakness comes from the fact that several persons left for our start-up *Probayes* during the evaluation period, and that this prospective research direction is mainly conducted by one permanent researcher.

For the next four years, we will continue to work on the two research directions respectively related to "Bayesian robot programming" and to "Bayesian modeling of living systems"(see section 5). We will also address a new and very prospective issue : how can the central nervous system implement probabilistic computation ?

3 Knowledge dissemination

3.1 Publications

This section should count the publications of the project-team. A bibliography at the end of this document (sorted by category), should list in extenso all the publications denoted here. The project-team will select a few "major" publications that will be available on the evaluation seminar web site. TBR.

	year1	year2	year3	year4
PhD Thesis	4	2	4	4
H.D.R (*)		1		
Journal	5	2	7	9
Conference proceedings (**)	14	27	22	22
Book chapter				
Book (written)				1
Book (edited)			1	4
Patent		2		
Technical report	7	13	4	2
Deliverable				

(*) HDR Habilitation à diriger des Recherches

(**) Conference with a program committee

Indicate the major journals in the field and, for each, indicate the number of papers coauthored by members of the project-team that have been accepted during the evaluation period.

Remark: The four first journals of the list are considered as journals of rank A by the GDR Robotique.

1. International Journal of Robotics Research (IJRR, IF=1.318)
2. IEEE Transactions on Robotics (IEEE TR0, IF=1.976)
3. IEEE Transactions on Intelligent Transportation Systems (IEEE ITS, IF=1.689)
4. Autonomous Robots (IF=1.413)
5. Field Robotics (IF=0.960)
6. Robotics and Autonomous Systems (RAS, IF=0.633)
7. Advanced Robotics (IF=0.504)

Indicate the major conferences in the field and, for each, indicate the number of papers coauthored by members of the project-team that have been accepted during the evaluation period.

Remark: The five first conferences of the list are considered as conferences of rank A by the GDR Robotique.

1. IEEE International Conference on Robotics and Automation (ICRA, 42%)
2. IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS, 47%)
3. International Symposium of Robotics Research (ISRR)
4. IEEE International Symposium on Intelligent Vehicle (IV, 29% + posters)
5. Robotics Science and Systems (RSS, 25%)
6. International Symposium of Experimental Robotics (ISER)
7. International Conference on Field and Service Robotics (FSR, 44%)
8. IEEE International Conference on Intelligent Transportation Systems (ITS, 57%)

3.2 Software

ProBT.

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.

In order to perform pre-test and to provide help for Cycab developers, a robot simulator has been developed. This simulator simulate both 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. It also includes realistic models of various sensors such as Laser scanners, Cameras, Catadioptric cameras, GPS ... All these models rely on state-of-the-art GPU techniques, allowing the simulator to assign the CPU time to the applications.

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.

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 software is available on the INRIA Forge (`http://gforge.inria.fr/projects/cycabtk`).

Bayesian Occupation Filter (BOF) Toolbox.

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 no.0552735 and no. 0552736 (September 2005), and is commercialized by our start-up *ProBayes*. This toolbox has been used in several developments done for large industrial companies such as Toyota, Denso, or Hitachi.

ColDetect.

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.

Grid Occupany Wavelets (GROW).
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.

Markov models toolbox.
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.

3.3 Valorization and technology transfert

Start-up Probayes. Based on the results obtained in the field of Bayesian Programming, we have launched our start-up *Probayes* in october 2003. *Probayes* is now in charge of the development and the commercialization of the Bayesian Programming approach and of the *ProBT* inference engine. The company is also in charge of the development of the related industrial applications. The current main fields of applications are: finance (fraud and corruption detection, operational risk, stock picking), automotive industry (driver assistance systems), healthcare (assistance to blind and elderly people), sale force (price fixing, sale prevision, stock management and intelligent marketing), security and defense.

It should be noticed that very close relationship still exist between *e-Motion* and *Probayes*. Indeed, most of the technical leaders of the company are coming from our project-team (especially Emmanuel Mazer the CEO), Pierre Bessière is a co-founder of the company, and several researchers from *e-Motion* are (or have been) scientific consultants for the company. More over, we are involved in several common R&D projects and technological tranfers.

Patented and commercialized technology : Bayesian Occupancy Filter. The *Bayesian Occupancy Filter (BOF)* has been patented in 2005, and integrated one year later into the *ProBT* library of *Probayes* under a licensing agreement with INRIA.

An other patent extend the *BOF* concept to the domain of Driving Assistance System. This technology aims at making a robust perception of the dynamic environment of a vehicle. It basically relies on a Bayesian Filtering process which is applied on a probabilistic discretized model of the environment state space (i.e. space and velocities). In this method, the filtering process takes explicitly into account the sensor model (one or several sensors), the history of the measurements, and the dynamic model of the sensed objects. It has been designed in order to be as robust as possible to temporary occlusions and sensor errors.

Industrial impact. The *BOF* has been identified as a promising technology by some large industrial companies of the automotive industry (in particular Toyota and Denso who was visiting several European research laboratories in 2005 and 2006). After a first successful evaluation of the technology by Toyota and by Denso (under short-term contracts), we have signed two long-term collaboration contracts with these companies (contracts involving our start-up *Probayes*). Thanks to the success of the collaboration, the R&D contract with Toyota has recently been extended for a fifth year collaboration. We are also currently processing data provided by IBEO (a car supplier from Germany), in order to evaluate the performances of the *BOF* technology on the IBEO Lidar product. It should be noticed that the *BOF* technology has also been used by *Probayes* in some other industrial contracts (e.g. for Hitachi).

In case of success, our technology might have a great impact on the next generation of car safety systems.

3.4 Teaching

Indicate the number of hours spent in teaching activities on a yearly basis for each scientific staff member, where the teaching activities were carried out (Universities - DEUG, Licence, Maitrise, DESS, DEA -, Engineering schools. TBR.

Lecture "Robotics: Grand challenges, Research issues, and future Application domains"; Europe-Mexico Summer school on "Image and Robotics" (SSIR) (Every year since 2000). *Teacher: C. Laugier.*

Tutorial on "Safe Navigation in Dynamic and Open Environments"; Singapore, November 2005. *Teachers: C. Laugier and O. Aycard.*

Lecture "Autonomous Robots"; International Master MOSIG (M2), INPG, Grenoble (Since 2008). *Teachers: C. Laugier, O. Aycard, Th. Fraichard, A. Martinelli, P. Bessière.*

Lecture "Robotics and Computer Vision"; International Master MOSIG (M1), INPG, Grenoble (Since 2008). *Teachers: C. Laugier, O. Aycard, E. Boyer, E. Arnaud.*

Lecture "Basic tools and models for Robotics"; Cnam Grenoble (Every year). *Teachers: C. Laugier and J. Troccaz.*

Lecture "Robotics and motion autonomy"; DEA "Imagerie, Vision, Robotique" INPG, Grenoble (Every year until 2007). *Teacher: C. Laugier.*

Lecture on "Motion Planning"; Europe-Mexico Summer School on Image and Robotics (SSIR)(Every year since 2000). *Teacher: Th. Fraichard.*

Lecture on "Motion Planning"; INPG-UJF "Image, Vision & Robotics" Master course, Grenoble (Every year until 2007). *Teacher: Th. Fraichard.*

"Advanced Motion Planning", Invited course, Univ. of Zaragoza (ES), June 2006. *Teacher: Th. Fraichard.*

"Advanced Motion Planning"; Post-Master course, Mathematics Informatics INPG-UJF Doctoral School, Grenoble (2008). *Teacher: Th. Fraichard.*

Lecture "Knowledge Modelling and Processing"; Master of Computer Science 2nd year, University of Grenoble (every year) . *Teachers: MC. Rousset, J. Gensel, O. Aycard, E. Arnaud.*

Lecture "Machine Learning"; Master of Computer Science 1st year, University of Grenoble (every year). *Teachers: E. Gaussier, O. Aycard.*

Lecture "Machine Learning"; Master of Computer Science 2nd year, University of Grenoble (every year). *Teachers: G. Bisson, A. Douzal, A. Guerin, O. Aycard.*

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": Europe-Mexico Summer school on "Image and Robotics" (SSIR) (every year since 2000). *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 programming" course, Europe-Mexico Summer School on Image and Robotics (SSIR) (every year since 2000). *Teacher: P. Bessière.*

Lecture on Bayesian Approach to Process Control, Grenoble, France, Compagnie Générale de Chauffage, Janvier 2006. *Teacher: P. Bessière.*

Lecture on Bayesian Programming, BACS school 2006, Coimbra, Portugal, May 2006. *Teacher: P. Bessière.*

Lecture on Bayesian Approach to Banking Operational Risk, Paris, France, December 2004, March 2005 and June 2006. *Teacher: P. Bessière.*

Lecture on Bayesian Programming, SSIR 2006 (Summer School on Image and Robotics), Montpellier, France, juillet 2006. *Teacher: P. Bessière.*

Lecture on Bayesian model of perception, PSFMR 2006 (Perception and Sensor Fusion in Mobile Robotics, Fermo, Italy, September 2006. *Teacher: P. Bessière.*

Lecture on Bayesian Robot Programming, BIBA winter school 2005, London, January 2005. *Teacher: P. Bessière.*

Lecture on Bayesian Analysis (perception, probability, geometry), Math and Brain summer school, Paris, July 2005. *Teacher: P. Bessière.*

PostGrade lecture at EPFL on Bayesian Inference and Learning. 2005. *Teacher: P. Bessière*

3.5 Visibility

C. Laugier and J.M. Ahuactzin participate every year (since 2000) to the organizing committee of the Europe-Mexico Summer School on Image and Robotics (SSIR).

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 Intenational Conference on Intelligent Robots and Systems (IROS), International Conference on Field and Service Robotics (FSR). He was General chair of IROS'97, Regional programm chair of IROS'00, Programme chair of IROS'02, General Chair of FSR'07, Program Chair of IROS'08.

C. Laugier has organized the following workshops and published Books and Journal special issues related to these events :

- "Safe navigation in Dynamic environments; Application to driving assistance" in the scope of the IEEE/RSJ IROS'06 conference in Beijing (Oct. 2006).
- "Intelligent Transportation Systems" related to the IEEE Intelligent Vehicle conference 2006 in Tokyo (June 2006); this workshop has been organized in the scope of the ICT-Asia Network FACT.
- "Safe Navigation in Dynamic Environments I" in the scope of the IEEE ICRA'07 conference in Rome (Apr. 2007).
- "Safe Navigation in Dynamic Environments II" in the scope of the IEEE/RSJ IROS'07 conference in San Diego (Oct. 2007).
- "Safe Navigation in Dynamic Environments III" in the scope of the IEEE/RSJ IROS'08 conference in Nice (Sept. 2008).
- "Navigation in Dynamic Environments IV" in the scope of the IEEE ICRA'09 conference in Kobe (May 2008).

C. Laugier gave a number of invited talks:

- "Will future robots really share the human living space ?", Plenary talk at Singapore Robotics Games 2004 (SRG'04), Singapore, May 2004.
- "Bayesian approaches for autonomous mobile robots", Tokyo University, december 2007.
- "Present and Future of Robotics", Plenary panel session, ICARCV 2008, Hanoi, December 2008.
- "Perception-based navigation for autonomous vehicles in open and dynamic environments", Co-mobility Workshop, january 2008.
- "Dynamic and Human Environments: A real challenge for Robotics", Keynote at the FSR'09 conference (The International Conference 2009 on Field and Service Robotics), Cambridge, July 2009.

C. Laugier was the coordinator of the "FACT" ICT-Asia Network on ITS 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 co-chair (with U. Numes and A. Broggi) of the IEEE Technical Committee on "Intelligent Transportation Systems and Autonomous Vehicles" (since 2005).

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.

C. Laugier is on the evaluation panel of the EU FP7 ICT2009 CFP on Cognitive Systems and Robotics.

C. Laugier has been invited as "Chief Judge" at the Singapore Robotics Games 2004 (SRG'04).

C. Laugier, U. Numes , and A. Broggi have received in 2006 the IEEE RAS Award[8] *"Most active IEEE RAS Technical Committee"* for the activity of the IEEE Technical Committee on "Intelligent Transportation Systems and Autonomous Vehicles" they are co-chairing.

C. Laugier and A. Martinelli are guest editors for a special issue on IJRR journal (to be published in the first trimester of 2009)

C. Laugier and A. Martinelli are guest editors for a special issue on JFR journal (published in 2008)

A Martinelli is a member of the editorial board of the IEEE Transaction on Robotics (since November 2007)

O. Aycard was member of the programme committees of conferences on Robotics : CIRAS'2005, IEEE IV'2006, IEEE ITSC'2006, FSR'2007, IEEE ITSC'2007.

A. Spalanzani is member of the editorial committee of the In Cognito cognitive sciences journal. She is also a member of the ANR selection committee of the CONTINT program.

Th. Fraichard organised the France-Korea workshop on Advanced Driver Assistance Systems (ADAS), Paris, December 2005.

Th. Fraichard is a regular member of the programme committees of the ICRA and IROS conferences. In 2007, he was also a member of the following programme committee: Workshop on Planning, Perception and Navigation for Intelligent Vehicles, Roma (IT), Apr. 2007; Int. Symp. on Distributed Autonomous Robotic Systems (DARS), Tsukuba (JP), *Nov. 2008.*

Th. Fraichard gave a number of invited talks:

- "Safe motion planning in dynamic environments", Motion Planning in Virtual Environments workshop, Toulouse (FR), January 2005.

[8] 1000 US$ and a plaque given during the banquet of the IEEE ICRA conference 2006 in Orlando.

- “Motion Safety in Dynamic Environments, Safe Navigation in Open and Dynamic Environments”,Autonomous Systems versus Driving Assistance Systems workshop, Beijing (CN), October 2006.
- “Safe Motion in Dynamic Environments”, Univ. of Zaragoza (ES), June 2006.
- “Safety in Dynamic Environments”, Autonomous Sensor-Based Motion for Complex Robots in Complex Environments workshop, Orlando, FL (US), May 2006.

Pierre Bessière organized the “Bayesian Cognition” international workshop in Paris (January 2006) (see http://bayesiancognition.org). This workshop gathered 21 prestigious invited speakers of the field and an audience of 250 persons.

P. Bessière is a member of the editorial 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 IEE/IROS (International Conference on Intelligent Robots and Systems), Conference EA (International Conference on Artificial Evolution).

P. Bessière regularly reviews papers for the IEEE Transactions on Evolutionary Computation and Autonomous Robots journals.

P. Bessière gave an invited talk at ISRR 2007: “Bayesian Programming: life science modeling and robotics applications”, ISRR 2007, Japan.

4 External Funding

Indicate the budget allocated to your project-team in keuros (without taxes). BR

(k euros)	year1	year2	year3	year4
INRIA Research Initiatives				
ARC† H-Vis				1000
LSIA‡ XX				
National initiatives				
Predit Mobivip	27 200	36 000	27 200	
Predit Puvame	80 000	66 500	17 300	
Predit-ANR LoVe		14 600	52 600	65 000
FUI GRAAL (starting 2009)				
European projects				
IST Cybercars 2 (inclusing PhD scholarship)			15 000	24 000
IST IP Prevent	14 000	40 600	216 700	55 400
IST BIBA	122 300	60 800	16 500	
IST IP BACS-INRIA		93 600	240 300	187 150
IST Intersafe 2				3 500
IST Have-IT				3 000
IST SFLY (starting 2009)				
Associated teams				
XX				
Industrial contracts				
Gintic Singapore	7 500	7 000		
Denso 1 & 2			15 000	7 500
Toyota 1 & 2	5 000	125 000	95 000	95 000
Scholarships				
PhD * (EU MC “Visitor”)		30 000	30 000	30 000
Post Doc* (French Gov)			9 300	28 000
AI+				
Specialist Engineer (ArosDyn)#				5 700
Other funding				
ADT ArosDyn (Inria)				21 700
ICT-Asia FACT (Inria+Cnrs+Mae)	10 000	47 000	57 000	
IST IP BACS-CNRS		45 600	54 000	50 000
ACI Systemes complexes (Cnrs)	1 800	1 800	1 800	600
Robea Bayesian Models (Cnrs)	700	13 000		
Robea Parknav (Cnrs)	2 500	5 000	5 000	
PICS Singapore (Cnrs+ Mae)	5 000	7 500	5 000	
PAI Safemove korea	18 000	18 000		
Subvention SSIR (Inria+Cnrs)			10 000	8 000
Royalties Probayes				4 500
Total	294 000	612 000	867 700	600 050

† INRIA Cooperative Research Initiatives
‡ Large-scale Initiative Actions
∗ other than those supported by one of the above projects
+ junior engineer supported by INRIA
# engineer supported by INRIA

ARCs

ARC H-VIS (2008-2011)

Vision, Navigation, and Intentional Actions of Humanoid Robots. The partners of H-VIS are the Inria project-teams Lagadic, Bipop, Bunraku, and e-Motion; the LAAS-CNRS is also involved in H-VIS.The contribution of e-Motion concerns the vision-based navigation.

National initiatives

Predit "Puvame" [October 2003-September 2005]

National Predit Programme *Puvame* "Protection des Usagers Vulnérables par alarme et Manoeuvre d'Evitement". The partners of the project are: Inria *e-Motion* (coordinator), Inria *Imara*), Ecole des Mines de Paris, INRETS Lyon, Intempora, Probayes, Robosoft, Connex.

An important number of accidents between vulnerable road users and moving traffic could be avoided by improving the abilities of visibility and estimation of the situation by the driver, and by putting in action an alarm system addressed to the driver and the road user in danger. This project will contribute to reduce the number of accidents of this type, by developing the principal following functionalities: (1) Improvement of the abilities of perception of the driver in close and average distance environments by dated fusion; (2) Detection and estimation of the dangerous situations, by analyzing current data relating on the "behavior of the driver" and to the estimation result of the "dangerosity" of the operations in progress; (3) Activation of alert actions associated to vehicle and vulnerable users; (4)Integration and experiments on vehicles and preliminary study on bus and/or trams.

Predit "Mobivip" [October 2003-September 2005]

National Predit Programme *Mobivip* "Véhicules Individuels Publics pour la Mobilité en centre ville". The project gathers 5 laboratories and 7 industrials to implement, evaluate and demonstrate the NTIC impact on a new mobility service. More precisely, the goals are to implement:(1) a transportation service base on free-use vehicles, (2) a multimodal information system, (3) a toolbox for integration in global management policy at downtown scale.

Robea "Bayesian models for motion generation" [2003-05]

This project involves three partners : Inria *e-Motion* (leader), Inria *Evasion*, and Irisa *Siames*. The objective is to propose new forms of interaction between human and data-processing systems. The synthetic worlds created and managed by these systems can be populated by human actors and virtual actors controlled by computers. The approach that we propose consists in equipping the virtual entities in these environments with an autonomy of movement and action, as well as adaptability and reaction abilities to certain situations.

Robea "Parknav" [October 2002- September 2005]

This project gathers five partners : Inria *e-Motion* (leader), Inria *Movi* and *Prima*, Irisa *Vista*, and LAAS Toulouse. The goal of the project is to automate the driving of a vehicle moving amidst mobile obstacles (other vehicles, pedestrians) on a site equipped with a camera-based perception system. A joint demonstration integrating both the perception and the planning levels is scheduled in the last phase of the project. It will take place on the Inria Rhône-Alpes parking site which is currently being equipped with a multiple-camera perception system and will involve Cycab experimental vehicles.

Predit "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 (e-Motion, Arobas, Imara), CEA List, Université Paris Sud, CNRS/heudiasyc, LASMEA, Armines (CNN, CAOR)).

European projects

IST "Profusion" [2004-2008]

European IP project, *PreVENT* Programme(Preventive and Active Safety Applications); *Profusion* subproject, "Project for Robust and Optimised Perception by Sensor Data Fusion".The *PreVENT* consortium includes 70 partners coming from industry and public research (including the main car constructors), and *e-Motion* is the leader of the *Profusion* subproject.

By means of a horizontal approach through Preventive Safety functions requirements, and of the integrated assessment of the potential and performance of sensor technologies and sensor data fusion, the overall objective of ProFusion is to set the bases for Perception Solutions that will go beyond current state-of-the-art.As described here, ProFusion is the first stage of a horizontal activity within IP PReVENT, that will aim at: establishing a forum including representatives of specified vertical subprojects for exchanges on topics related to sensors and sensor data fusion, circulating, feeding back and synthesizing information exchanged, and exploiting the outcome from these exchanges to specify and propose one or more new horizontal subproject(s) with a technical content focussed on original research work of common interest in these fields, leading to tangible results.

IST-FET "BIBA" [November 2001- November 2005]

European project IST-2001-32115 "Bayesian Inspired Brain and Artefacts". The project involves five partners : Inria *e-Motion* (coordinator), University College of London (Gatsby Unit), University College of Cambridge (Physiology lab), Collège de France (Laboratory of Physiology of Perception and Action, A. Berthoz), Ecole Polytechnique Fédérale de Lausanne (Autonomous Systems Lab, R. Siegwart), and the Massachusetts Institute of Technology (Non Linear Systems Lab, JJ. Slotine). The twin technological and scientific goals of the *BIBA* project are the followings :(1) to reconsider in the light of Bayesian probabilistic reasoning our methodology, models,algorithms and techniques for building artefacts for the "real world"; (2) to provide a firm Bayesian basis for understanding how biological systems use probabilistic logic to exploit the statistical properties of their environments. The project is organised along 3 axes of research and development: (1) Neural basis of probabilistic inference; (2) New probabilistic models and algorithms for perception and action; (3) New probabilistic methodology and techniques for artefact conception and development.

IST "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 (www.cybercars.org) and CyberMove (`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.

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: (1) Inherently safe due to very low weight (¡500g) and appropriate propeller design; (2) Capable of vision-based fully autonomous navigation and mapping; (3) 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.

"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:(1) Design of the task repartition between the driver and co-driving system (ADAS) in the joint system; (2) Failure tolerant safe vehicle architecture including advanced redundancy management; (3) 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.

IST "BACS" [january 2006-february 2011]

Europen project FP6-IST-027140 BACS "Bayesian Approach to Cognitive Systems". 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" [1] which regroups 12 different PhD theses defended within the BIBA and BACS European projects.

Associated teams and other international projects

France-Mexico "Navdyn" [October 2003- October 2005]

The *NavDyn* project is a joint *Lafmi*[9] project between *e-Motion* and the Center for Intelligent System (CSI) of the Mexican Technological Institute of Monterrey (ITESM). The goal of the project is to develop basic tehnologies for the "Autonomous Navigation in Dynamic Environments". CSI Itesm is in charge of the vision part of the project (detection and tracking of moving objects using an off-board pan-tilt video camera), whereas *e-Motion* is in charge of the autonomous motion part (taking into account moving objects with unknown future behaviour). The midterm evaluation that took place in November 2003 was successful and the project was prolongated until October 2005.

France-Singapore "Neurophysiology and robotics" [June 2004- June 2008]

This CNRS-PICS project involving the Collège de France (LPPA), INRIA *e-Motion*, the University

[9]Lafmi is a France-Mexico laboratory in computer sciences

of Singapore (NUS), and the *IPAL* joint CNRS-NUS laboratory in Singapore. The objective is to study some aspects of the physiology of human vision, and to try to develop robotics models inspired from biological systems. An application of this research we will be to control a wheelchair from natural human control channels. This research involves a co-directed PhD student located in singapore.

France-Korea "SafeMove" [April 2004- April 2006]
The *SafeMove* project is a joint project in the scope of the France-Korea STAR programme. It aims at conducting common research activities in the area of Intelligent Transportation Systems (ITS) and Automated Guided Vehicles (AGV). The proposed project combines three research groups (two French: Inria and Lasmea Clermont-Ferrand, and one Korean: Sungkyunkwan University) having complementary skills and expertise to conduct research in the area of ITS and AGV, particularly focused on models and algorithms allowing for safe autonomous navigation in dynamic environments (like those found in a urban context).

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 is ledaded by *e-Motion*; it involves two INRIA project-teams (e-Motion and Imara), a CNRS laboratory (LASMEA Clermont-Ferrand), SungKyunKwan University (Korea), Shangai Giao Tong University (China), Nanyang Technological University (Singapore), and Tokyo University (Japan). Several international workshops, researchers exchanges, a journal special issue publication, and a public demonstration of three CyberCars in Shanghai have been produced as results of the project. Thanks to these results, the 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).

Industrial contracts

Toyota Motors Europe [2005] [2006-2009] [2009-2010]
The contract with Toyota Motors Europe is a joint collaboration involving Toyota Motors Europe, INRIA and ProBayes. It follows a first successful short term collaboration with Toyota in 2005. This contract aims at developing innovative technologies in the context of automotive safety. The idea is to improve road safety in driving situations by equipping vehicles with the technology to model on the fly the dynamic environment, to sense and identify potentially dangerous traffic participants or road obstacles, and to evaluate the collision danger. The sensing is performed using sensors commonly used in automotive applications such as cameras and lidar. This contract has recently been prolongated until February 2010.

Denso [2006][2007-2008]
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)[10] 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

[10]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.

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.

Other funding,

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. The output of *ArosDyn* will be a pre-industrial software for implementing some Driver Assistance functionalities in future commercial cars.

5 Objectives for the next four years

The objectives for the next four years are roughly in continuation of the current three main research directions of *e-Motion*. Both the results and the evolution of the previous objectives have been discussed in the sections 2.4, 2.5, and 2.6. Most of the new objectives are related to the deliverables of our current and new research contracts. Each individual research topic will involve at least one PhD student.

5.1 Objective 1 : Dynamic world Perception and understanding

The work on the three main issues (Dynamic world perception, Localization and mapping, Prediction and Risk assessment) will be continued during the next four years. As it has been mentioned in section 2.4.6, we will put more effort on the solving of the related efficiency and robustness problems:

- *Improved grid-based Bayesian filtering.* We will try to improve our approach (efficiency, accuracy, memory requirement), by both studying algorithmic improvements and possible hardware solutions (e.g. GPU implementation and SOC). The success of this last point will depend on the success of the envisaged collaboration with the CEA.
- *Robust detection and tracking.* Concerning the object detectors, it is clear that no perfect generic detector exists. We will focus on the *Bayesian fusion* of specialized detectors or of weak detectors, which are easier to develop, potentially more efficient, and potentially able to produce more robust combined results. Concerning the tracker, we have started to study a new promising approach aiming at considering the detection and tracking functions as a single process; this approach should lead to improve the robustness of the tracker.
- *Accurate and efficient localization and mapping.* We will continue to develop the mathematical tools and algorithmic models which are required for improving the localization and mapping functions (in particular for complex 3D environments and multi-modal data). The long term objective is to design hybrid maps and SLAM algorithms, by coupling our feature based approach with an optimized grid based representations.

- *Risk assessment.* We will continue to develop this important concept, by using Gaussian Process and Prediction functions for estimating at any time the risk of future potential collisions. We will generalize this representation to more complex traffic scenes, and we will study how to automatically learn such types of models. This work is mainly done in the scope of the long-term Toyota collaboration. We will also study, in synergy with the objective 2 (Motion Planning), how this concept could be used in a probabilistic Motion Planner.

5.2 Objective 2 : Motion planning and Autonomous Navigation in the Real World

Four key sub-objectives are proposed for this research direction:

- *Probabilistic Inevitable Collision States (ICS).* So far, we have considered ICS based upon a deterministic model of the future. This is hardly compatible with the uncertain environment assumption; it is therefore important to further explore the ICS concept and to shift to a probabilistic representation.

- *Trajectory Deformation.* It remains to be experimentally validated.

- *Partial Motion Planning (PMP).* First, the coupling of PMP with ICS needs to be explored in order to determine if navigation in open and dynamic environments *with safety guarantees* can actually be achieved. There is no need to stress that if autonomous robotic systems are ever to be deployed among human beings, such guarantees will be of the utmost importance.

- *PMP & Bayesian risk estimation.* The goal is to explicitly take into account the Uncertainty and Dynamicity characteristics of the real world, for making safe goal-oriented navigation decisions. The idea is to use a continuous Bayesian interpretation of the dynamic situation (risk factor), in order to take at any time the safest navigation decisions. This last sub-objective will require a tighter cooperation with the activities carried out in Objective 1 (Dynamic world perception and understanding).

5.3 Objective 3 : Bayesian approach to Cognitive Systems

For the next four years, we will continue to work on the two research directions respectively related to "Bayesian robot programming" and to "Bayesian modeling of living systems":

- *Bayesian robot programming.* We will focus on the modeling and the learning of sensory-motor skills. A first work will be done in the scope of the industrial project GRAAL, with the objective to implement the resulting Bayesian sensory-motor models on a commercial ludic humanoid robot. A more prospective work will be done in the scope of the EU BACS project and of the INRIA AEN[11] PAL ("Personnaly Assisted Living"), which will probably involve most of the robotics project-teams from INRIA; our contribution will be on the share control of a semi-autonomous wheelchair (safe navigation capabilities and multi-modality interactions between the transported human and the wheelchair).

- *Bayesian modeling of living systems.* We will continue to work on this prospective research direction, in collaboration with our neurophysiologists partners (in particular in the scope of the PhD thesis of Estelle Gilet supported by the EU BACS project).

[11] Action d'Envergure Nationale

We will also start to address a new and very prospective issue : how can the central nervous system (CNS) implement probabilistic computation ? A very preliminary work has already been done in collaboration with Jacques Droulez from LPPA Collège de France on the hypothesis that "probabilistic computation in the CNS could take place at the molecular level". We have already shown that some equilibrium between population of alosteric macromolecules (for instance, ionic canals) and their corresponding messengers (for instance Ca^{++}) can be described by a Bayesian filter (see Audrey Houillon, Cosyne paper - 2009 and several BACS deliverables). An ANR proposal has been submitted on this topic.

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