Evaluation of Inria theme Robotics and Intelligent Environments

Project-team FLOWERS

March 2017

Project-team title: FLOWERS

Scientific leader: Pierre-Yves Oudeyer

Research centers: Inria Bordeaux Sud-Ouest

Common project-team with: Ensta ParisTech

1 Personnel

Current composition of the project-team (december 2016):

Research scientists and faculty members:

- Pierre-Yves Oudeyer (Team leader), Research director (DR1), Inria
- David Filliat (Professor), Ensta ParisTech
- Anna-Lisa Vollmer, Starting Research Position, Inria

Associate research scientists and faculty members:

- Manuel Lopes, Univ. Lisbon, Portugal

Research Engineers:

- Damien Caselli, Inria
- Yoan Mollard, Inria
- Stéphanie Noirpoudre, Inria
- Didier Roy, Inria
- Théo Segonds, Inria

Ph.D. students:

- Baptiste Busch, Inria
- Thibaut Munzer, Inria
- Thibault Desprez, Inria
- Benjamin Clément, Inria
- Céline Craye, Ensta ParisTech
- Yuxin Chen, Ensta ParisTech
- Alexandra Delmas, Inria
- Florian Golemo, Inria
- Adrien Matricon, Inria
- Alvaro Ovalle Castaneda, Inria
- Gennaro Raiola, Ensta ParisTech
- William Schueller, Inria

Administrative assistant:

- Nathalie Robin

Current position of former project-team members

Former senior researchers

- Manuel Lopes, currently Professor at Univ. Lisboa, Portugal.
- Freek Stulp, currently head of Department of Cognitive Robotics at DLR, Germany.
- Alexander Gepperth, currently Professor at Univ. Fulda, Germany

Former PhD students:

- Adrien Baranes, PhD 2009-2013, currently at Google, Inc.
- Mai Nguyen, PhD 2010-2014, currently assistant professor (tenure track), at ENST Bretagne, Brest, France.
- Jonathan Grozou, PhD 2012-2014, currently group leader in Lee Cronin's lab, Univ. Glasgow, Scotland.
- Olivier Mangin, PhD 2010-2014, currently postdoc at Yale University, Brian Scasselati's lab, US.
- Fabien Benureau, PhD 2011-2014, currently postdoc at Inria, Mnemosyne team, France.
- Thomas Cederborg, PhD 2009-2013, currently Postdoc at Georgia Tech (Charles Isbell's lab).
- Natalia Lyubova, PhD 2010-2013, currently Research Engineer at Softbank Robotics, Issy les Moulineaux
- Louis-Charles Caron, PhD 2012-2015, currently Electronics Engineer, Switzerland
- Guillaume Duceux, PhD 2011-2015, currently Research Engineer at Keecker, Paris
- Alexandre Armand, PhD 2011-2016, currently Research Engineer at Renault, Guyancourt

Former postdocs:

- Thomas Degris, postdoc 2012-2013, currently senior researcher at Google Deepmind, London.
- Clément Moulin-Frier, postdoc 2012-2014, currently research engineer at Cogitai, US.
- Panagiotis Papadakis, post-doc 2014-2016, assistant professor (tenure track), at ENST Bretagne, Brest.

Former engineers:

- Pierre Rouanet, engineer 2013-2016, currently co-founder of Pollen Robotics startup company.
- Matthieu Lapeyre, engineer, 2014-2016, currently co-founder of Pollen Robotics startup company.
- Nicolas Rabault, engineer, 2014-2016, currently co-founder of Pollen Robotics startup company.
- Antoine Hoarau, engineer 2012-2014, currently Research Engineer at UPMC, Paris

Last INRIA enlistments

- Manuel Lopes (CR1, 2010), now Professor at Univ. Lisbon, Portugal (through Inria detachment), and associate researcher of the Flowers team.
- Anna-Lisa Vollmer (SRP, 2014). From march 2017, she will be postdoc at Univ. Bielefeld, and associate researcher of the Flowers team.

2 Research goals and results

2.1 Keywords

developmental robotics, lifelong autonomous learning, reinforcement learning, machine learning, cognitive development, cognitive science, developmental psychology, neuroscience, intrinsic motivation, curiosity, active exploration, active learning, active teaching,social learning, human-robot interaction, sensorimotor development, language acquisition, perceptual learning, representation learning, open-source robot platforms, educational technologies, open science.

2.2 Context and overall goals of the project

Developmental processes allow humans, and especially infants, to continuously acquire novel skills and adapt to their environment over their entire lifetime. They learn autonomously, through self-exploration and social interaction with their peers, and without the need for an engineer to open and retune the brain and the environment specifically for each new task. Machines and robots have been so far very far from such developmental capabilities, even for life-long learning of relatively simple sensorimotor skills.

Human and biological sciences have identified various families of developmental mechanisms that are key to explain how infants can acquire so robustly a wide diversity of skills [Joh11, Mil04], in spite of the complexity and high-dimensionality of the body [Ber67a] and the open-endedness of its potential interactions with the physical and social environment.

Our long-term goal, framed within the field of Developmental Robotics [WMP$^+$01, LMPS03] [Oud11], is focused on the study of selected developmental mechanisms in embodied machines along two strands:

Strand 1: Lifelong autonomous learning in robots. Understanding how developmental mechanisms can be functionally formalized and transposed in robots and explore how they can allow robots to acquire open-ended repertoires of skills through self-exploration and social interaction. Besides this fundamental question, we study the combination of these techniques with classical robot engineering techniques, and their application to the new field of personal robotics, where robots need to adapt to complex high-dimensional sensorimotor spaces as well as to non-expert users in everyday environments.

Strand 2: Robot models as tools to understand human development in cognitive sciences. The computational modelling of life-long learning and development mechanisms achieved in the team centrally targets to contribute to our understanding of the processes of sensorimotor, cognitive and social development in humans. In particular, it provides a methodological basis to analyze the dynamics of the interaction across learning and inference processes, embodiment and the social environment, allowing to formalize precise hypotheses and later on test them in experimental paradigms with animals and humans. A paradigmatic example of this activity is the Neurocuriosity project achieved in collaboration with the cognitive neuroscience lab of Jacqueline Gottlieb, where theoretical models of the mechanisms of information seeking, active learning and spontaneous exploration have been developped in coordination with experimental evidence and investigation, see `https://flowers.inria.fr/neurocuriosityproject/`.

Through these two research strands, there are strong bi-directional interactions with two families of scientific fields:

- Developmental Robotics reuses techniques from and provides application to two distinct sub-fields of Robotics: "Robot Learning" and "Human-Robot Interaction", which respectively investigate how statistical machine learning techniques can allow a robot to acquire novel skills (but are not necessarily bio-inspired and do not consider mechanisms for the

continuous development of novel skills over extended periods of time), and how one can design interaction and interfaces which permit natural, intuitive and social interaction between robots and non-expert users;
- Developmental Robotics formalizes theories from and provides new models to sciences studying developmental processes: "Developmental psychology", "Cognitive Developmental Neuroscience" and "Linguistics", which all investigate the same phenomena of behavioral, cognitive and social development using different methodological and conceptual apparatuses. Developmental Robotics aims at complementing those apparatuses with computer and robotic models.

Developmental processes are highly diverse and complex [Joh11, Mil04]. Thus, our research focuses on selected key questions and developmental mechanisms that allow for efficient open-ended learning of novel sensorimotor and interaction skills in embodied systems. In particular, we study constraints that guide exploration and skill acquisition in large and unknown sensorimotor spaces:
- Mechanisms of intrinsically motivated exploration and active learning, including artificial curiosity, allowing in particular to self-organize developmental trajectories and collect efficiently learning data;
- Mechanisms of adequately constrained optimization and statistical inference for autonomous sensorimotor skill acquisition (e.g. for optimizing motor policies in real robots);
- Mechanisms for social learning, e.g. learning by imitation or demonstration, which implies both issues related to machine learning and human-robot interaction;
- Constraints related to embodiment, in particular through the concept of morphological computation, as well as the structure of motor primitives/muscle synergies that can leverage the properties of morphology and physics for simplifying motor control and perception;
- Maturational constraints which, coupled with the other constraints, can allow the progressive release of novel sensorimotor degrees of freedom to be explored;

We also study how these constraints on exploration can allow a robot to bootstrap multimodal perceptual abstractions associated to motor skills, in particular in the context of modeling language acquisition as a developmental process grounded in action.

Among the developmental principles that characterize human infants and can be used in developmental robots, FLOWERS focuses on the following three principles:
- **Exploration is progressive.** The space of skills that can be learned in real world sensorimotor spaces is so large and complicated that not everything can be learned at the same time. Simple skills are learned first, and only when they are mastered, new skills of progressively increasing difficulty become the behavioral focus;
- **Internal representations are not only innate but also learned and adaptive.** For example, the body map, the distinction self/non-self and the concept of "object" are discovered through experience with initially uninterpreted sensors and actuators; Internal representations and concepts are rarely purely perceptual, but fundamentally rely on actions and affordances;
- **Exploration can be self-guided and/or socially guided.** On the one hand, internal and intrinsic motivation systems regulate and organize spontaneous exploration; on the other hand, exploration can be guided through social learning and interaction with caretakers.

2.3 Application Domains

Beyond the fundamental research in developmental robotics and computational modelling of human development in cognitive sciences, the Flowers team studies applications in several domains:

Personal and lifelong learning robotics Many indicators show that the arrival of personal robots in homes and everyday life will be a major fact of the 21st century. These robots will range from purely entertainment or educative applications to social companions that many argue will be of crucial help in our society. Yet, to realize this vision, important obstacles need to be overcome: these robots will have to evolve in unpredictable homes and learn new skills in a lifelong manner while interacting with non-engineer humans after they left factories, which is out of reach of current technology. In this context, the refoundation of intelligent systems that developmental robotics is exploring opens potentially novel horizons to solve these problems. In particular, this application domain requires advances in artificial intelligence that go beyond the current state-of-the-art in fields like deep learning. Currently these techniques require tremendous amounts of data in order to function properly, and they are severaly limited in terms of incremental and transfer learning. One of our goals is to drastically reduce the amount of data required in order for this very potent field to work. We try to achieve this by making neural networks aware of their knowledge, i.e. we introduce the concept of uncertainty, and use it as part of intrinsically motivated multitask learning architectures, and combined with techniques of learning by imitation.

Human-Robot Collaboration. Robots play a vital role for industry and ensure the efficient and competitive production of a wide range of goods. They replace humans in many tasks which otherwise would be too difficult, too dangerous, or too expensive to perform. However, the new needs and desires of the society call for manufacturing system centered around personalized products and small series productions. Human-robot collaboration could widen the use of robot in this new situations if robots become cheaper, easier to program and safe to interact with. The most relevant systems for such applications would follow an expert worker and works with (some) autonomy, but being always under supervision of the human and acts based on its task models.

Environment perception in intelligent vehicles. When working in simulated traffic environments, elements of FLOWERS research can be applied to the autonomous acquisition of increasingly abstract representations of both traffic objects and traffic scenes. In particular, the object classes of vehicles and pedestrians are if interest when considering detection tasks in safety systems, as well as scene categories ("scene context") that have a strong impact on the occurrence of these object classes. As already indicated by several investigations in the field, results from present-day simulation technology can be transferred to the real world with little impact on performance. Therefore, applications of FLOWERS research that is suitably verified by real-world benchmarks has direct applicability in safety-system products for intelligent vehicles.

Educational technologies:

- Personalization in Intelligent Tutoring Systems Algorithms for optimal and active teaching, based on computational models of curiosity-driven learning, can be applied for personalization of pedagogical activities (e.g. which exercize or which cue to propose to each student at the right time) in educational software systems used in schools and at home. From a practical perspective, improved models could be saving millions of hours of students' time (and effort) in learning. These models should also predict the achievement levels of students in order to influence teaching practices.
- Educational Robotics: A major societal challenge is educating the youngest to understanding the digital world and becoming actors. To reach this goal, it is important to design educational material that fosters motivating, cooperative and playful conceptual and practical experience. The use of robotics has the potential to be a useful medium to teach computing skills to children, being at the same time stimulating and rich of many important concepts where the digital world connects to the real world. In this context, the Flowers team developps pedagogical kits, deployed in French schools ($>$ 15000 schoolchildren using the kits developped in the team) for the initiation to robotics and computer science. It provides a micro-world for learning, and takes an enquiry-based educational approach, where kids are led to construct their understanding through practicing an active investigation methodology within teams.

2.4 Research axis 1: Active exploration: intrinsic motivations, curiosity and maturation in robots

Personnel

Pierre-Yves Oudeyer, Manuel Lopes, David filliat, Freek Stulp, Clément Moulin-Frier, Mai Nguyen, Sébastien Forestier, Fabien Benureau, Yoan Mollard, Thibaut Muntzer

Scientific achievements and positioning

Intrinsic motivations are mechanisms that drive spontaneous curiosity-driven exploration in animals and humans, for whom they are central to organizing autonomous and open-ended acquisition of novel skills and knowledge [25, 40, 38]. We have played a central role in introducing, formalizing and transposing technically this concept in robotics and artificial intelligence [37, 16, 25, 40], and using this formalization to impact the understanding of these concepts in cognitive sciences and neuroscience [25, 40, 38, 49, 34].

Figure 1: The experimental setup presented during NIPS 2016 conference which showcases our results on curiosity-driven exploration

Active exploration in robotics and artificial intelligence. Through the successive elaboration of algorithmic architectures of intrinsically motivated exploration and learning based on the formalisms of reinforcement learning and bandit algorithms (IAC [OK06, OKH07a], R-IAC [BO10a, LO12b], SAGG-RIAC [16], McSAGG-RIAC [BO10b], SGIM [37], SGIM-ACTS [NO12a], MACOB [87], HACOB [86]), modelling various mechanisms for empirical estimation of learning progress (including in a Bayesian unified framework [126]) in synergy with complementary techniques (maturation [BO10b], learning by imitation [37], sensorimotor primitives [163], incremental regression techniques for high-dimensions [CLBO10]), and their experimentation in various real and simulated robots, and with the collaboration of several colleagues and students, we have explained and demonstrated how these techniques can be key in addressing two related fundamental challenges in robot development and learning:

- How can an autonomous robot learn continuously novel reusable skills by its own initiative and without needing that an engineer reprograms a new specific cost function to be optimized for each new task [OKH07a]?
- How can a robot acquire autonomously, efficiently and robustly new skills, involving the learning of forward and inverse models in large high-dimensional inhomogeneous sensorimotor spaces [16, 41]? (Forward models, denoted (S(t), A(t)) $\rightarrow$ S(t+1), where S(t) is the state of the embodied machines at time t and A(t) encodes the parameters of action primi-

tives, allow a robot to predict the consequences of its actions in given contexts -e.g. how an object moves when pushed in a given manner-, and inverse models $T_\theta \rightarrow \Pi_\theta$ allow a robot to determine which policy of action $\Pi_\theta : S \rightarrow A$ to use in order to achieve objective T_θ in its task space, typically defined over S -e.g. which push movement to make in order to have an object move in a given way-);

In particular, we achieved several milestone results:

- **Intrinsically motivated learning in real robots:** Intrinsically motivated exploration and learning of multiple skills can be scaled to high-dimensional real world robots [37, 16]; The IAC algorithm in the Playground Experiment [OKH07a] was the first intrinsic motivation system in the literature to be shown to scale to real world robots as well as to continuous state and action spaces, and the team continued to be a leader at the international level in using intrinsic motivation architectures in real robots, showing how it can allow to learn control of flexible bodies [37, 16], and shown by the demonstration showed at NIPS 2016 which obtained the 2nd best demonstration award [172].
- **Autonomous lifelong learning:** With only one general task-independent cost function that drives curiosity-driven learning of high-dimensional forward and inverse models, a robot can learn a varied and organized repertoire of reusable motor skills [25, 40] which otherwise require hand-tuned ad hoc specific cost functions in other existing technical approaches (e.g. [EMM+08, KP09, RGHL09]);
- **Efficient multitask learning in high-dimensional spaces:** We have shown that our models of intrinsically motivated multitask reinforcement learning (considering continuous fields of parameterized RL problems) allow very efficient learning in high-dimensional inhomogeneous continuous action spaces, being much more efficient than classical active exploration techniques (such as those searching for maximal uncertainty or entropy). This result, as illustrated in qualitative and quantitative studies, is due to the fact that real world sensorimotor spaces have properties which are incompatible with the assumptions of traditional active learning heuristics [163]. We have also shown that generalized inverse models acquired through curiosity-driven exploration can be re-used robustly to achieve skills specified later on (for example by a human) [16, 37]. Moreover, learning multiple parameterized RL tasks through intrinsic motivations is often more efficient than learning a single RL problem when rewards are rare or deceptive, and explains why recent state-of-the-art work in Deep Reinforcement Learning has reused this algorithmic technique either directly [BSO+16, KNST16] or indirectly through the concept of auxiliary tasks [SMAD16] to solve RL problems that were previously unsolvable.
- **Generalization of active learning to strategic, modular and hierarchical learning: active selection of what, when, how and from whom to learn:** We have proposed a generalized active learning algorithmic framework, called strategic learning [LO12a], which allows robots to active and incrementally choose what, when, how and from whom to learn [NO12b]. In particular, this has allowed to shift the view of active learning research (which so far considered active learning as the problem of selecting which actions/stimulus to sample in order to observe its effect/label) towards a generalized view where active exploration algorithms choose which parameterized reinforcement learning problem to focus on at any given moment, and what learning algorithm to use to solve them [102]. This can also allow robots/agents to choose when to ask the help of a teacher, which teacher to ask from if there are several teachers, what to ask her, and how to use this information REFS. In particular, this framework has allowed us to instantiate three major new curiosity-driven algorithmic architectures:
  - **Active goal/problem exploration:** We have shown that instead of actively sampling low-level actions, sampling parameterized RL problems (goals in robot tasks) based on measures of competence progress enabled a considerable gain in efficiency [16, 164].

Other related approaches are closely relate to this framework, such as intrinsically motivated option learning [BSC04], as well as the more recently developed MAP-Elite algorithm in evolutionary computation [CCTM15], [18].

  - **Combination of active goal exploration and imitation learning:** with the SGIM-ACTS architecture, we have elaborated algorithms for active and autonomously combining self-exploration of goals and imitation learning, showing that very little human guidance could allow to bootstrap and accelerate curiosity-driven learning of complex skills [NO12b, 27].
  - **Modular and hierarchical intrinsically motivated goal exploration:** We have developed a new family of active exploration algorithms based two concepts: 1) active model babbling, where the learner selects spaces in which to sample parameterized RL problems (then using goal exploration); 2) modular and/or hierarchical representation of parameterized spaces, allowing to group problem spaces in structures which reflect the modular/hierarchical structure of the environment. Based on these concepts, the MACOB [87] and HACOB [86] architectures were shown to scale intrinsically motivated multitask learning to very complex environments, and allowing the learning of tools-objects-hands affordances [172].

- **Active exploration for transfer learning:** we also elaborated algorithms exploiting the measure of learning progress (or associated measures of behavioral diversity) to enable transfer learning across tasks which do not share the same effect spaces, and showed that this can allow to considerably increase the speed of exploration and learning of new parameterized task spaces [18].

Contributions to policy gradient and model learning algorithms The curiosity-driven active exploration algorithms presented above drive the incremental active collection of new data through experimentation. At the low-level of these architectures are algorithms for learning forward/inverse models, and/or improving the parameters the policies to solve parameterized tasks. In this perspective, we have also made several key contributions to these families of algorithms, including:

- **A Unified Model for Regression** Regression is the process of learning relationships between inputs and continuous outputs from example data, which enables predictions for novel inputs. Regression lies at the heart of imitation learning, and value function approximation for reinforcement learning. In [54, 131], we provide a novel perspective on regression, by distinguishing rigoroulsy between the models and representations assumed in regression, and the algorithms used to train the parameters of these models. A rather surprising insight is that many regression algorithms (Locally Weighted Regression, Receptive Field Weighted Regression, Locally Weighted Projection Regression, Gaussian Mixture Regression, Model Trees, Radial Basis Function Networks, Kernel Ridge Regression, Gaussian Process Regression , Support Vector Regression Incr. Random Features Regularized Least Squares, Incr. Sparse Spectrum Gaussian Process Regr., Regression Trees, Extreme Learning Machines.) use very similar models; in fact, we show that the algorithm-specific models are all special cases of a "unified model". This perspective clearly seperates between representations and algorithms, and allows for a modular exchange between them, for instance in the context of evolutionary optimization.
- **Relationship between Black-Box Optimization and Reinforcement Learning** Policy improvement methods seek to optimize the parameters of a policy with respect to a utility function. There are two main approaches to performing this optimization: reinforcement learning (RL) and black-box optimization (BBO). In recent years, benchmark comparisons between RL and BBO have been made, and there has been several attempts to specify which approach works best for which types of problem classes. We have made several contributions to this line of research by: 1) Defining four algorithmic properties that further clarify

the relationship between RL and BBO. 2) Showing how the derivation of ever more powerful RL algorithms displays a trend towards BBO. 3) Continuing this trend by applying two modifications to the state-of-the-art Pi^2 algorithm, which yields an algorithm we denote *PiBB*. We show that *PiBB* is a BBO algorithm, and, more specifically, that it is a special case of the state-of-the-art CMAES algorithm. 4) Demonstrating that the simpler *PiBB* achieves similar or better performance than Pi^2 on several evaluation tasks. 5) Analyzing why BBO outperforms RL on these tasks. These contributions have been published in [160, 52].
- **Simultaneous On-line Discovery and Improvement of Robotic Skill Options** The regularity of everyday tasks enables us to reuse existing solutions for task variations. For instance, most door-handles require the same basic skill (reach, grasp, turn, pull), but small adaptations of the basic skill are required to adapt to the variations that exist (e.g. levers vs. knobs). In a joint project with Laura Herlant of Carnegie Mellon University, we developed the algorithm "Simultaneous On-line Discovery and Improvement of Robotic Skills" (SODIRS) that is able to autonomously discover and optimize skill options for such task variations [142]. We demonstrate SODIRS' performance in simulation, as well as on a Meka humanoid robot performing the ball-in-cup task.
- **Deterministic Policy Gradient Algorithms** Thomas Degris (Flowers team) and colleagues from UCL and Google Deepmind have considered deterministic policy gradient algorithms for reinforcement learning with continuous actions [140] . The deterministic policy gradient has a particularly appealing form: it is the expected gradient of the action-value function. This simple form means that the deterministic policy gradient can be estimated much more efficiently than the usual stochastic policy gradient. To ensure adequate exploration, we introduced an off-policy actor-critic algorithm that learns a deterministic target policy from an exploratory behaviour policy. We demonstrated that deterministic policy gradient algorithms can significantly outperform their stochastic counterparts in high-dimensional action spaces.

Software and hardware Following an open-science approach, the team develops the Explauto open-source python library and associated Jupyter notebooks allowing to replicate many of these technical results [129]. This Explauto library, as well as the Poppy Humanoid robot platform developped by the team (see below), were used to make a demonstration at NIPS 2016 which obtained the 2nd best demor award: `https://www.youtube.com/watch?v=NOLAwD4ZTWO`. This hardware/software platform will be reused in the next years for further evaluation of intrinsically motivated multi-task reinforcement learning algorithms.

Positioning Conceptually, the contribution strongly contrasts with most of existing work in machine and robot learning in one important respect: it is usually assumed that an engineer pre-programs a cost function specific to each new task, and researchers try to build optimization/learning methods without assuming particular properties of the cost function [EMM$^+$08, KP09, RGHL09]. With intrinsic motivation, one introduces the idea that a single general cost function can be used to learn a large variety of tasks and skills (which can then be reused later on for specific tasks required by the human user), and that the efficiency of optimization methods developed in previous research could be considerably enhanced by adequate design of this cost function. Other researchers have been elaborating similar ideas in different fields: J. Schmidhuber had elaborated conceptually similar models in machine learning [Sch91], A. Barto has been exploring similar question in reinforcement learning [SBC04], and Karl Friston has studied them under the light of a normative theoretical Bayesian framework [FFR$^+$16]. Yet, our models were quite different in the technical details and our successive architectures were the only one to be scalable and evaluated with real robots and continuous state and action spaces. Intrinsic motivation techniques have also relationships with techniques in active learning and optimal experiment design [CGJ96, Fed72]. Yet, because of the specific properties of the sensorimotor spaces of developmental robots (high-dimensions, unlearnability, unboundedness, limited life-time), none of the techniques of active learning and statistics can be used and scaled to this domain. Thus, we had to introduce new technical ideas for solving those challenges. The algorithms and architectures for intrinsically motivated exploration are complex and it required substantial work to end up with systems that could scale up to the real world. This can be seen through the fact that few other teams in the world came up with models running on real-world continuous robot sensorimotor spaces. This was also emphasized by our 2nd best demonstration award at NIPS 2016, showing live online learning mechanisms in large sensorimotor spaces and with physical interaction with non-expert users.

Impact and collaborations The team played a central role in setting intrinsic motivation as a central scientific topic in robotics and artificial intelligence, and many other researchers are now citing and both conceptually and technically reusing this work. The set of our articles related to this topic is cited 2216 times (source: Google scholar, oct. 2016), and each year between 10 and 20 percent of the articles in the main conference (IEEE ICDL-Epirob) in our domain cites at least one of these articles. This impact is also shown by the reuse of these concepts in recent major AI and machine learning projects, including industrial labs. In particular, these algorithmic ideas are now being reused by several major private AI labs, who have used them to solve difficult deep reinforcement learning problems with rare or deceptive rewards. More than 20 laboratories in the world now build robot learning systems re-implementing variants of the associated algorithms. We have been invited to give keynote lectures on this topic in high-audience international conferences Evostar 2015 (Denmark), Devoxx 2015 (France), BICA 2015 (France), AAAI Fall Symposium 2013 (US), AAAI Spring Symposium 2014 (US), WACAI 2014 (France).

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2.5 Research axis 2: Models of curiosity and intrinsic motivation in humans and monkeys (Cognitive science)

Personnel

Pierre-Yves Oudeyer, Manuel Lopes, Clément Moulin-Frier, Sébastien Forestier, Pierre Rouanet

Scientific achievements and positioning

In complement of the advances in artificial intelligence and robotics presented in the previous section, we have also formalized and conducted robotic experimentation of theories of intrinsic motivation to contribute to the development of novel theories and experimental paradigms to understand intrinsic motivation and curiosity in humans, in strong collaboration with developmental psychology and neuroscience. These collaborations involve in particular the Neurocuriosity project (both an associated team and an HFSP grant) with cognitive neuroscientists Jacqueline Gottlieb (Univ. Columbia, NY, US) and developmental psychologist Celeste Kidd (Univ. Rochester, US), as well as another collaboration with developmental psychologist Linda Smith (Univ. Indiana, Bloomington, US). Through these collaborations, we proposed the following novel insights and contributions back into these disciplines:

- **General formal framework to model active exploration, intrinsic motivation/curiosity and information seeking in humans and animals.** While existing investigations examined curiosity in qualitative, descriptive terms, we have proposed a novel unified formal framework that integrates quantitative behavioral and neuronal measures with computationally defined theories of (Bayesian) Reinforcement Learning and decision making [38, 25, 162, 35].

- **Role of curiosity/intrinsinc motivation in development and evolution.** Infants' own activities create and actively select their learning experiences. In a collaboration with Linda Smith, we have analyzed recent models of embodied information seeking and curiosity-driven learning and have showed that these mechanisms have deep implications for development and evolution. In [40], we have discussed how these mechanisms yield self-organized epigenesis with emergent ordered behavioral and cognitive developmental stages. Fundamental aspects of developmental trajectories, defined as the successive formation of stages of behavioural and cognitive structures of increasing complexity, can be self-organised as a side-effect of the dynamical interactions between intrinsically motivated learning, the body and the environment [38, 40, 49, 34, 25];
- **The interaction between intrinsic motivation and imitation in development.** We have shown that the discovery and learning of social skills such as imitation and the first steps of speech and language can be generated as a result of general mechanisms of intrinsically motivated learning, and that in return imitation learning could influence the structure of curiosity-driven exploration [34, 40].
- **Formal link between learning progress and dopaminergic circuits.** We have proposed new hypotheses related to how empirical measure of learning progress in the brain could be achieved by dopaminergic circuits [38, 25].
- **New experimental paradigms to study free active exploration in humans.** A vast majority of behavioral and neural studies to date have focused on decision making in reward-based tasks, but the rules guiding intrinsically motivated exploration remain largely unknown. To examine this question we developed a new paradigm for systematically testing the choices of human observers in a free play context. Behavioural experiments in humans allowed us to discover new factors that influence intrinsically motivated learning: task difficulty, novelty and the size of the search space [14, 124]. These experimental paradigms are now at the center of a new HFSP Neurocuriosity project where we will systematically compare behavioral results with predictions of our formal models.
- **Predictive information of eye movements to infer curiosity states.** We conducted the first experimental study of the relation between eye movements and state curiosity, associated with a data mining analysis [15]. This allowed us to show that certain (previously unstudied) features of eye movements can allow a machine to predict the state of curiosity of subjects (in a cross-subject manner) with good accuracy, and that most information in eye movement was in anticipatory movements. This is suggesting potential practical applications for educational technologies, recommender systems and research in cognitive sciences.
- **Intrinsically motivated oculomotor exploration guided by uncertainty reduction and conditioned reinforcement in non-human primates.** Using a novel oculomotor paradigm, combined with reinforcement learning (RL) simulations, we have showed that monkeys are intrinsically motivated to search for and look at reward-predictive cues, and that their intrinsic motivation is shaped by a desire to reduce uncertainty, a desire to obtain conditioned reinforcement from positive cues, and individual variations in decision strategy and the cognitive costs of acquiring information. The results suggest that free-viewing oculomotor behavior reveals cognitive and emotional factors underlying the curiosity driven sampling of information. These results were published in [35], and additional results are under review in PNAS (current state: accepted with minor revision).
- **Role hierarchical intrinsically motivated learning in the development of tool use.** In [86, 173], we presented the HACOB (Hierarchical Active Curiosity-driven mOdel Babbling) architecture of algorithms that actively chooses which sensorimotor model to train in a hierarchy of models representing the environmental structure. We showed that using a hierarchical structure of sensorimotor models and active model babbling as an intrinsic motivation

to explore sensorimotor models that have a high learning progress, overlapping phases of behaviours are autonomously emerging in the developmental trajectories of agents. This is reproducing aspects, as well as questioning other aspects, of experimental observations on infant tool learning in the developmental psychology litterature, such as the work of Siegler and colleagues [Sie89]. To our knowledge, this is the first model of curiosity-driven development of simple tool use and of the self-organization of overlapping phases of behaviours. In particular, our model explains why and how intrinsically motivated exploration of non-optimal methods to solve certain sensorimotor problems can be useful to discover how to solve other sensorimotor problems, in accordance with Siegler's overlapping waves theory, by scaffolding the learning of increasingly complex affordances in the environment.

Maturation: adaptive control of body complexity in robots and humans To harness the complexity of their high-dimensional bodies during sensorimotor development, infants are guided by patterns of freezing and freeing of degrees of freedom. We have formulated and studied computationally the hypothesis that such patterns, such as the proximodistal freeing of degrees of freedom when learning to reach, can emerge spontaneously as the result of a family of stochastic optimization processes, without an innate encoding of a maturational schedule. In particular, we presented simulated experiments with a 6-DOF arm where a computational learner progressively acquires reaching skills through adaptive exploration, and we show that a proximodistal organization appears spontaneously, which we denote PDFF (ProximoDistal Freezing and Freeing of degrees of freedom). We also compared the emergent structuration as different arm structures are used – from human-like to quite unnatural ones – to study the effect of different kinematic structures on the emergence of PDFF. Preliminary results were published in [SO12a, SO12b], and current results are presented in a paper submitted to the Developmental Science journal (current status: accepted with minor revision). In addition, we have shown that the freeing and freezing of DOFs in robots could be actively controlled and driven by measures of learning progress described above, and proposed an algorithmic architecture integrating intrinsic motivation and maturation, showing that it was extremely efficient in large unbounded sensorimotor spaces [164].

2.5.1 Impact and collaborations

This work directly impacted research in psychology and neuroscience, in particular through direct collaborations and joint publications with high-profile psychologists (e.g. Linda Smith, Indiana Univ.) and neuroscientists (Jacqueline Gottlieb, Univ. Columbia, NY, US, through the Neurocuriosity Associate team and HFSP project Curiosity). These collaborations lead to a major milestone publication [25] presenting a unified theoretical landscape about curiosity in neuroscience and machines, published in the most prestigious cognitive science journal (TICS, impact factor: 16,5). In the context of these interdisciplinary collaborations, we also co-initiated and co-coordinated the organization of the First and of the Second Interdisciplinary Symposium on Information Seeking, Curiosity and Attention (2014: Bordeaux; 2016: London, 150 participants), and we are co-editor of a special issue on models of speech acquisition in the prestigious Journal of Phonetics.

External support

This research axis benefitted from the following funding sources: Inria Neurocuriosity Associated Team grant, ERC Starting Grant Explorers, HFSP Grant Neurocuriosity, PhD grant from Ecole Normale Supérieure.

2.6 Research axis 3: Computational Models of Language Acquisition in robots and humans

Personnel

Pierre-Yves Oudeyer, David Filliat, Clément Moulin-Frier, Anna-Lisa Vollmer, Thomas Cederborg, Jonathan Grizou, Olivier Mangin, William Schueller, Yuxin Chen.

Scientific achievements and positioning

What are the mechanisms needed to learn language? How is it possible that children learn language so easily and with apparently poor linguistic input? How can a robot guess the meaning of a new word? How are the social regulation mechanisms involved in language learning? How can one draw the attention of a robot towards particular aspects of their environment? What are the interactions between acquisition mechanisms and language evolution?

We investigate the mechanisms that enable humans and robots to learn new words and to use them in appropriate situations. We have built a number of robotic and computational experiments studying the mechanisms of concept formation, joint attention, social coordination and language games, and articulating the roles of learning, physical and environmental biases in language acquisition. The unifying theme of all these experiments is development: we explore the hypothesis that language can only be acquired through the progressive structuring of the sensorimotor and social experience.

Modeling the role of intrinsic motivation/curiosity and stochastic learning in speech and language development

- **Models of the vocal development in infants** We have bridged the gap between two issues in infant development: vocal development and intrinsic motivation. We proposed and experimentally tested the hypothesis that general mechanisms of intrinsically motivated spontaneous exploration, also called curiosity-driven learning, can self-organize developmental stages during early vocal learning and explain several aspects observed in infants. We introduced a computational model of intrinsically motivated vocal exploration [127, 34, 42], which allows the learner to autonomously structure its own vocal experiments, and thus its own learning schedule, through a drive to maximize competence progress. This model relies on a physical model of the vocal tract, the auditory system and the agent's motor control, as well as vocalizations of social peers. We present computational experiments that show how such a mechanism can explain the adaptive transition from vocal self-exploration with little influence from the speech environment, to a later stage where vocal exploration becomes influenced by vocalizations of peers. Within the initial self-exploration phase, we showed that a sequence of vocal production stages self-organizes, and shares properties with data from infant developmental psychology: the vocal learner first discovers how to control phonation, then focuses on vocal variations of unarticulated sounds, and finally automatically discovers and focuses on babbling with articulated proto-syllables. As the vocal learner becomes more proficient at producing complex sounds, imitating vocalizations of peers starts to provide high learning progress explaining an automatic shift from self-exploration to vocal imitation.
- **Emergent Jaw Predominance in Vocal Development through Stochastic Optimization** Infant vocal babbling is strongly relying on jaw oscillations, especially at the stage of canonical babbling, which underlies the syllabic structure of world languages. We have proposed, modelled and analyzed a hypothesis to explain this predominance of the jaw in early babbling. This hypothesis states that general stochastic optimization principles, when applied

to learning sensorimotor control, automatically generate ordered babbling stages with a predominant exploration of jaw movements in early stages, just like they generate proximo-distal organization of exploration in arm reaching as described in the paragraph above. In particular, such stochastic optimization principles predominantly explore jaw movement at the beginning of vocal learning, and when close to the rest position of the vocal tract, as it impacts the auditory effects more than other articulators. Results presenting this work are described in a paper submitted to IEEE TCDS (accepted with minor revisions) and preliminary results are described in [177].

Models and experiments to study how the structure of social interaction supports language acquisition/formation

- **Pragmatic frames in human-human and human-robot teaching interactions** Addressing the challenge of robot learning of communication skills from inexperienced human users, we proposed 'pragmatic frames' as flexible interaction protocols that provide important contextual cues to enable learners to infer new action or language skills and teachers to convey these cues. Following the concept developed in the field of developmental linguistics [BW83, Fil82, Tom03], we defined a pragmatic frame to be an interaction protocol negotiated over time between interaction partners. We further specify a Pragmatic Frame to especially involve an observable *coordinated sequence of behaviors* and also relevant *cognitive operations*. In a paper published in Frontiers in Psychology [46], we have given a theoretical account of pragmatic frames as an alternative to the mapping metaphor which posits that children learn a word by mapping it onto a concept of an object or event. Word learning with pragmatic frames occurs as children accomplish a goal in cooperation with a partner. We elaborated on pragmatic frames, offered initial parametrizations of the concept, and embedded it in current language learning approaches. Aiming at leveraging the concept of pragmatic frames for Human-Robot Interaction, we published an article in Frontiers in Neurorobotics [56] in which we studied a selection of state-of-the-art HRI work in the literature which has focused on learning–teaching interaction and analyzed the interactional and learning mechanisms that were used in the light of pragmatic frames. This has allowed us to identify new key challenges to be addressed in HRI that have not been considered so far in the literature.
- **Experimental study of how interaction protocols are negotiated in collaborative tasks with humans** Targeting to advance the flexibility of HRI and robot learning from unknown human signals, we investigated the processes used by humans to negotiate a protocol of interaction when they do not already share one. We developed an innovative experimental setup, where two humans have to collaborate to solve a task. The channels of communication they can use are constrained and force them to invent and agree on a shared interaction protocol in order to solve the task. These constraints allow us to analyze how a communication protocol is progressively established through the interplay and history of individual actions. The setup has been presented at the IEEE ICDL-EpiRob conference [146].
- **Alignment to robot actions** Alignment is a phenomenon observed in human conversation: Many aspects of dialog partners' behavior converge and mutually adapt. Such alignment has been proposed to be automatic and the basis for communicating successfully. Recent research on human-computer dialog promoted a mediated communicative design account of alignment according to which the extent of alignment is influenced by interlocutors' beliefs about each other. Our work in which participants interacted with the iCub humanoid robot is the first to investigate alignment of manual actions in HRI and results which have been published in the Int. Journal of Social Robotics [55] confirmed that alignment also takes place in the domain of actions.

Models of statistical cross-situational learning of concepts in multimodal sensorimotor flows

- **Multi-modal concept acquisition.** We introduced MCA-NMF, a computational model of the acquisition of multi-modal concepts by an agent grounded in its environment [31, 122]. Our model finds patterns in multimodal sensor input that characterize associations across modalities (speech utterances, images and motion) using the Nonnegative Matrix Factorization algorithm. We illustrated this framework by showing how a learner discovers word-like components from observation of gestures made by a human together with spoken descriptions of the gestures, and how it captures the semantic association between the two [122] and extended this approach to associating objects with their names.
- **Cross-situational word learning.** Learning word meanings during natural interaction with a human faces noise and ambiguity that can be solved by analysing regularities across different situations. We propose a model of this cross-situational learning capacity by extending our MCA-NMF approach and apply it to learning nouns and adjectives from noisy and ambiguous speeches and continuous visual input. We presented experiments on learning object names and color names showing the performance of the model in real interactions with humans, dealing in particular with strong noise in the speech recognition [74]. We also compared its performance with Latent Dirichlet Association, a topic model with similar capabilities than NMF and show that theses approaches can be coupled with intrinsic motivations for the learner to actively choose the learning samples in order to enhance learning speed [73].
- **Solving ambiguities in imitation and language learning.** We identified a strong structural similarity between the Gavagai problem in language acquisition and the problem of imitation learning of multiple context-dependent sensorimotor skills from human teachers [19]. In both cases, a learner has to resolve concurrently multiple types of ambiguities while learning how to act in response to particular contexts through the observation of a teacher's demonstrations. We argued that computational models of language acquisition and models of motor skill learning by demonstration have so far only considered distinct subsets of these types of ambiguities, leading to the use of distinct families of techniques across two loosely connected research domains. We present a computational model, mixing concepts and techniques from these two domains, involving a simulated robot learner interacting with a human teacher. Proof-of-concept experiments showed that: 1) it is possible to consider simultaneously a larger set of ambiguities than considered so far in either domain; 2) this allows us to model important aspects of language acquisition and motor learning within a single process that does not initially separate what is "linguistic" from what is "non-linguistic". Rather, the model shows that a general form of imitation learning can allow a learner to discover channels of communication used by an ambiguous teacher.

Models of language formation in groups of individuals

- **General theoretical framework integrating development and evolution of speech** In [42], we studied scientific challenges for understanding development and evolution of speech forms. Based on the analysis of mathematical models of the origins of speech forms, including recent models based on Bayesian approaches to which we contributed [33, 32], we studied the fundamental question of how speech can be formed out of non-speech, at both developmental and evolutionary scales. In particular, we emphasized the importance of embodied self-organization, as well as the role of mechanisms of motivation and active curiosity-driven exploration in speech formation. Finally, outlined and evolutionary-developmental perspective of the origins of speech.
- **Role of active learning and active teaching in language game dynamics** How do linguistic conventions emerge among a population of individuals? A shared lexicon can self-organize at population level through local interactions between individuals, what has been

shown in the Naming Games computational framework. However, the dynamics of the convergence towards this shared convention can differ a lot, depending on the interaction scenario. Infants, who acquire social conventions really fast, control actively the complexity of what they learn, following a developmental pathway. Adults also adapt the complexity of their linguistic input when speaking to language beginners. We have elaborated models [138, 139] that allowed us to show that such active learning mechanism can improve considerably the speed of language formation in Naming Game dynamics. We compared two scenarios for the interactions: either the speaker exherts an active control, or the hearer does. The latter scenario shows faster dynamics, with more robustness.

Impact and collaborations

This research axis has benefitted from successful international collaborations. Research on alignment of actions was carried out in collaboration with Angelo Cangelosi, Plymouth University, UK [55]. The strand of work on interaction protocols and pragmatic frames was carried out in close collaboration with psycholinguist Katharina Rohlfing, Paderborn University, Germany and roboticist Britta Wrede, Bielefeld University, Germany. It has yielded impact in robotics, psychology and linguistics through two journal publications in Frontiers in Psychology and Frontiers in Neurorobotics [46, 56] and one conference paper at the main conference of the field (IEEE ICDL-EpiRob) [146]. These publications form an initial basis for a French-German ANR-DFG funded project around the research topic of pragmatic frames for which a joint proposal has been prepared during the evaluation period.

External support

This work benefitted from the following funding sources: ERC Starting Grant Explorers, PhD grants from Ecole Polytechnique and Chinese research government, Region Aquitaine.

Self assessment

The fundamental research topics of interaction dynamics and interactional processes which we study in light of language acquisition have been addressed in our research through human-human and human-robot interaction studies. Although these studies imply a rather high effort in terms of work and time, this line of research and especially the setups we built, bear high potential to advance several fields of research also in other disciplines. We thus plan on continuing this research and applying our existing setups to other research questions for example related to the development of an AI benchmark or the diagnosis of ASD.

2.7 Research axis 4: Interactive learning and human-robot interaction

Personnel

Manuel Lopes, Pierre-Yves Oudeyer, Freek Stulp, Matthieu Lapeyre, Thibaut Munzer, Yoan Mollard, Baptiste Busch, Jonathan Grizou, Pierre Rouanet, Stephanie Noirpoudre, Gennaro Raiola

Scientific achievements and positioning

In order to learn efficiently from interactions with humans who are not engineers, robots (and more generally machines such as in BCI systems [J37B,C61]) need sophisticated learning and perceptual algorithms as well as well designed interfaces. Indeed, robots eventually learn based on the training data they collect through social human-robot interaction. Thus, the quality of this data, as well as the efficiency of inference made from this data, is crucial. The vision that we have built and explored is that considerable learning efficiency can be gained by jointly designing interactive learning algorithms and using adequate human-robot interfaces, i.e. interfaces that are both easy to learn by the human, easy to use (e.g. do not require supervised labelling or calibration phases), and constrain the interaction so that the robot gets seamlessly high-quality training examples from a non-expert user. We have made several complementary contributions to solve these challenges:

Figure 2: Example of interactions considered in the 3rdHand project where the robot helps the user during an assembly task.

Interactive learning algorithms

- **Inverse reinforcement learning algorithms in Relational Domains:** We introduced a first approach to the Inverse Reinforcement Learning (IRL) problem in relational domains [130]. IRL has been used to recover a more compact representation of the expert policy leading to better generalization among different contexts. Relational learning allows to represent problems with a varying number of objects (potentially infinite), thus providing more generalizable representations of problems and skills. We showed how these different formalisms can be combined by modifying an IRL algorithm (Cascaded Supervised IRL) such that it handles relational domains. Our results indicated that we can recover rewards from expert data using only partial knowledge about the dynamics of the environment. We evaluated our algorithm in several tasks and studied the impact of several experimental conditions such as: the number of demonstrations, knowledge about the dynamics, transfer among varying dimensions of a problem, and changing dynamics.
- **Integrating learning by demonstration, learning by feedback and knowledge transfer** In [125] we studied how robot programming can be made more efficient, precise and intuitive if we leverage the advantages of complementary approaches such as learning from demonstration, learning from feedback and knowledge transfer. We designed a system that, starting from low-level demonstrations of assembly tasks, is able to extract a high-level relational plan of the task. A graphical user interface (GUI) then allows the user to iteratively correct the acquired knowledge by refining high-level plans, and low-level geometrical knowledge of the task. A final process allows to reuse high-level task knowledge for similar tasks in a transfer learning fashion. We conducted a user study with 14 participants asked to program assembly tasks of small furniture (chair and bench) for validation. The results showed that this combination of approaches leads to a faster programming phase, more precise than just demonstrations, and more intuitive than just through a GUI.
- **Relational Activity Processes for Modeling Concurrent Cooperation** In human-robot collaboration, multi-agent domains, or single-robot manipulation with multiple end-effectors, the activities of the involved parties are naturally concurrent. Such domains are

also naturally relational as they involve objects, multiple agents, and models should generalize over objects and agents. We proposed a novel formalization of relational concurrent activity processes that allows us to transfer methods from standard relational MDPs, such as MonteCarlo planning and learning from demonstration, to concurrent cooperation domains. We formally compare the formulation to previous propositional models of concurrent decision making and demonstrate planning and learning from demonstration methods on a real-world human-robot assembly task. A paper summarizing this research has been publish to the *International Conference on Robotics and Automation* (ICRA) 2016 [145].

- **Interactive Behavior Learning for Cooperative Tasks** This work goal is to propose a method to learn cooperative behavior to solve a task while performing the task with the user. The proposed approach reuses previous work on policy learning for Relational Activity processes (RAP). The main differences are: i) formulating the problem as a cooperative process. In MDP and RAP, it is assumed that there is one central decision maker. However, in a cooperation both the robot and the operator are taking decisions. ii) estimating the confidence. A Query by Bagging approach has been used where many policies are learned from a subset of the data. Their potential disagreement allows quantifying the confidence. iii) using the confidence for autonomous acting and for query making. Based on the confidence, the robot either directly acts or asks confirmation before acting.
  Results show that using an interactive approach require less instruction from the user while producing a policy that makes fewer mistakes. We developed a robotic implementation using a Baxter robot. A first article resulting from this work focusing on interactive preferences learning has been submitted to the *International Conference on Robotics and Automation* (ICRA) 2017 and a video demonstration can be view at : `https://vimeo.com/182913540`. We also conducted a user study to evaluate the impact of interactive learning on naïve users acceptation and performances.
- **Legible Motion** In a human-robot collaboration context, understanding and anticipating the robot intentions ease the completion of a joint-task. Whereas previous work has sought to explicitly optimize the legibility of behavior, we investigate legibility as a property that arises automatically from general requirements on the efficiency and robustness of joint human-robot task completion. Following our previous work on legibility of robot motions [141], we have conducted several user experiments to analyze the effects of the policy representation on the universality of the legibility.
- **Postural optimization for a safe and comfortable human-robot interaction** When we, humans, accomplish a task our body posture is (partially) constrained. For example, acting on an object constrains the pose of the hand relatively to the object, and the head faces the object we are acting upon. But due to the large number of degrees of freedom (DOF) of the human body, other body parts are unconstrained and several body postures are viable with respect to the task. However, not all of them are viable in terms of ergonomics. Using a personalized human model, observational postural assessment techniques can be automatized. Optimizing the model body posture is then the logical next step to find an ergonomically correct posture for the worker to accomplish a specific task.
  To optimize the subject's model to achieve a specific task, we define an objective function that minimizes the efforts of the whole body posture, based on the Rapid Entire Body Assessment (REBA) technique [HM00]. The objective function also accounts for visibility of the target object and worker's laterality. We have also implemented an automatic assessment of the worker's body posture based on the REBA method.
  Using a spherical object carried by a Baxter humanoid robot we mimic an industrial scenario where the robot helps the worker by positioning and orienting an object in which the worker has to insert specific shapes. In a user-study with forty participants, we compare three different robot behaviors, one of them being the result of the postural optimization of the

subject's personalized model. By the mean of a survey session, and the online assessment of the subject's posture during the interaction, we prove that our method leads to a safer posture, and is perceived as more comfortable.

- **Simultaneous learning of teaching signals and tasks in HRI** Interactive learning deals with the problem of learning and solving tasks using human instructions. It is common in human-robot interaction, tutoring systems, and in human-computer interfaces such as brain-computer ones. In most cases, learning these tasks is possible because the signals are predefined or an ad-hoc calibration procedure allows to map signals to specific meanings. We addressed the problem of simultaneously solving a task under human feedback and learning the associated meanings of the feedback signals [99, 97, 94, 98]. This has important practical application since the user can start controlling a device from scratch, without the need of an expert to define the meaning of signals or carrying out a calibration phase. We proposed an algorithm that simultaneously assign meanings to signals while solving a sequential task under the assumption that both, human and machine, share the same a priori on the possible instruction meanings and the possible tasks.

Intuitive human-robot interfaces While learning algorithms can be highly useful to learn the particularities of human teaching and interaction preferences, it is also crucial that humans are able to understand and guide robots in a transparent manner. This is especially relevant for humanoid/animaloid robots whose appearance often triggers wrong cognitive expectations where users interpret inacurately what the robot (can) sees or understands. Thus, the design of human-robot interfaces, channeling signals from the human to the robot and vice versa, can have a large impact on both usability and teaching efficiency:

- **Design of humanoid morphologies for HRI with the open-source 3D printed Poppy Humanoid platform**: we developed the first worldwide open-source 3D printed humanoid platform, allowing to study rapidly how various morphologies can impact motor control and human-robot interaction (Poppy Project, http://www.poppy-project.org, [8, 114, 113, 115, 112, 110, 111]). For example, in [110], we discuss the motivation and challenges raised by the desire to consider the morphology as an experimental variable on real robotic platforms as well as allowing reproducibility and diffusion of research results in the scientific community. In this context, we presented an alternative design and production methodology that we have applied to the conception of Poppy humanoid, the first complete 3D printed open-source and open-hardware humanoid robot. Robust and accessible, it allows exploring quickly and easily the fabrication, the programming and the experimentation of various robotic morphologies. Both hardware and software are open-source, and a web platform allows interdisciplinary contributions, sharing and collaborations. Finally we conduct an experiment to explore the impact of four different foot morphologies on the robot's dynamic when it makes a footstep. We show that such experimentation can easily be achieved and shared in couple of days at almost no cost. In the Poppy Education project, we have shown at a large scale how the Poppy Humanoid platform, as well as the Poppy ErgoJr platform (low-cost 3D printed robot based on Poppy technology), could be used in real classrooms for educational activities with children (including physical interaction in dance classes), see [8, 111, 179].
- **Multiple Virtual Guides** In co-manipulation, humans and robots solve manipulation tasks together. Virtual guides are important tools for co-manipulation, as they constrain the movement of the robot to avoid undesirable effects, such as collisions with the environment. Defining virtual guides is often a laborious task requiring expert knowledge. This restricts the usefulness of virtual guides in environments where new tasks may need to be solved, or where multiple tasks need to be solved sequentially, but in an unknown order. To this end, we have proposed a framework for multiple probabilistic virtual guides, and demonstrated

a concrete implementation of such guides using kinesthetic teaching and Gaussian mixture models [133, 134] . Our approach enables non-expert users to design virtual guides through demonstration.

- **Mediator interfaces** Use and study of the impact of mediator interfaces such as smartphones and laser pointers for robust teaching of novel words and objects to a robot [47].

Applications for calibration-free Brain-Computer Interfaces (BCI) Leveraging techniques developped initially for HRI [26, 99, 97, 96, 95], we developed an new approach for self-calibration BCI for reaching tasks using error-related potentials. The proposed method exploits task constraints to simultaneously calibrate the decoder and control the device, by using a robust likelihood function and an ad-hoc planner to cope with the large uncertainty resulting from the unknown task and decoder. The method has been evaluated in closed-loop online experiments with 8 users using a previously proposed BCI protocol for reaching tasks over a grid. The results show that it is possible to have a usable BCI control from the beginning of the experiment without any prior calibration. Furthermore, comparisons with simulations and previous results obtained using standard calibration hint that both the quality of recorded signals and the performance of the system were comparable to those obtained with a standard calibration approach.

2.7.1 Impact and collaborations

The Poppy robot platforms gather a community of $>$ 600 users/contributors on the forum (`https://forum.poppy-project.org`), is commercially distributed by the Generation Robots company, is used in $>$ 15 lycées in France, by 4 dance companies in their official shows. Some of its underlying technologies are now being exploited in the start-up company Pollen Robotics, spin-off of the team. Poppy has been presented in highly visible and prestigious wide audience venues (François Hollande at Elysée, Axelle Lemaire in Bordeaux, Sénat, Le Web conference, Tedx Cannes), in numerous high quality media/press articles (full pages in Le Monde, Les Echos, Libération, interviews on France Inter, France Info as well as in international press such as Scientific American, El Mundo, japanese TV, `lhttps://www.poppy-project.org/in-the-press/`), allowing millions of persons to discover aspects of the activities of Inria. It was featured in the report of "Stratégie Nationale de Recherche France 2020". The platform was selected as finalist for the Global Fab Award 2014, (`https://www.fab10.org/en/awards`) which select the best worldwide projects in the Makers ecosystem.

The mediator-based interfaces were evaluated and used by the general public continuously during several months at Cap Sciences museum in Bordeaux, and were reported in several general public newspapers and radios (with a video report on LeMonde.fr and Universciences), and resulted in one patent.

The Semi-Autonomous 3rd-Hand Robot allowed to created a research community and collaboration with University of Stuttgart, Tecnical University of Darmstadt, University of Innsbruck, and INESC-ID Lisbon. Several new technologies and scientific results were achieved with the software and datasets being available. Results include intuitive human-robot collaboration and measures of comfort for safe collaboration [130, 125, 66]. Several companies showed interest in (parts) of the research project and are currently sponsoring phd thesis, e.g. Bosch, Honda and Toyota.

The work on BCI was made under a collaboration with the University of Zaragoza. It was the result of using methods developed for intuitive interaction to provide important contributions to a completely different domain. It gave the opportunity to start new collaboration on the domains that include biological signals.

External support

The Semi-Autonomous 3rdHand Robot project was funded under the FP7 ICT programme. This research axis also benefitted from funding from ERC Starting Grant Explorers, from Région Aquitaine and from Inria.

2.8 Research axis 5: Autonomous perceptual and representation learning

Personnel

David Filliat, Alexander Gepperth, Pierre-Yves Oudeyer. Post-Doc: Cem Karaoguz, Michael Garcia Ortiz, Mathieu Lefort, Panagiotis Papadakis. PhD: Celine Craye, Clement Masson, Adrien Matricon, Louis-Charles Caron, Guillaume Duceux, Natalia Lyubova, Alexandre Armand

Scientific achievements and positioning

Note: The research axis "Computational models of language acquisition" includes many works of the team related to representation learning. Here, we include work on representation learning that is not related to language acquisition.

In this axis, we address both fundamental problems such as developing new learning approaches for autonomously discovering concepts and practical applications related to perception in autonomous or interactive scenarios.

- **Exploiting actions to learn visual concepts** In this research axis, led by David Filliat, we developed approaches to take advantages of robot actions capabilities in order to improve learning of concepts related to vision. The first approach was presented in [10], and consists of a visual system for a humanoid robot that allows to continuously and incrementally learn entities through interaction with a human partner in a first stage before categorizing these entities into objects, humans or robot parts and using this knowledge to improve objects models by manipulation driven by intrinsic motivations in a second stage [121, 30]. During the PhD of Celine craye, we developed an approach to learn top-down object-based visual saliency incrementally during environment exploration. This approach was shown to outperform state of the art object saliency algorithm and has been applied to a bio-inspired robotic head [80] and a mobile robot [81, 82]. We also proposed RL-IAC, an approach based on reinforcement learning and intrinsic motivations, that make a compromise between learning progress and action cost that was not negligible in our application [83].
- **Learning action models** We introduced COCOTTE (COnstrained Complexity Optimization Through iTerative merging of Experts), an iterative algorithm for discovering discrete, meaningful parameterized skills and learning explicit models of them from a set of behavior examples. We show that forward-parameterized skills can be seen as smooth components of a locally smooth function and, framing the problem as the constrained minimization of a complexity measure, we propose an iterative algorithm to discover them. This algorithm fits well in the developmental robotics framework, as it does not require any external definition of a parameterized task, but discovers skills parameterized by the action from data [123]. We also investigated algorithms that would be able to learn relevant visual or multi-modal features from data recorded while the robot performed some task. Among the many existing approaches, most of them currently using deep-learning, we explored the use of gated auto-encoders [185], a particular kind of neural networks including multiplicative connections, as they seem well adapted to this problem. Preliminary experimentation have been carried out with gated auto-encoders to learn transformations between two images. We showed

that Gated Auto-Encoders (GAE) can successfully find compact representations of simple transformations such as translations, rotation or scaling between two small images.

- **Autonomous concept discovery** This activity, led by Alexander Gepperth, aims at providing appropriate learning algorithms for developmental robotics fulfilling several requirements: being online and incremental, do not suffer from catastrophic forgetting effects, being generative (they extract underlying variables from data, what we term "concept formation"), and be at most weakly or self-supervised (without using human supervision). To this end, we developed the PROPRE algorithm which fulfills, by its combination of a generative and a discriminative part, all of the aforementioned requirements. It consists on the combination of three modules: a topological projection of each data flow on a self-organizing map; a decentralized prediction of each projection activity from each other map activities; a predictability measure that quantifies the prediction error. We have applied this approach to visual pedestrian detection during the Post-Doc of Mathieu Lefort and Cem Karaoguz[116, 117, 153] and to 3D gesture recognition during the PhD of Thomas Kopinsky [120], validating its incremental learning capacity in high dimensions [90, 24] and complementing it with a short-term memory in order to enhance is reactivity to changes in data [24]. We also worked on extending this approach in a hierarchical fashion to be able to perform deep learning during the PhD of Thomas Hecht[150, 151]
- **Environment mapping and navigation** Finally, as a continuation of work started before the FLOWERS team creation by David Filliat, we developed several approaches to perform semantic mapping of indoor environment. The goal is to produce maps that contain high-level information such as the presence of objects instead of only the obstacle or landmark position. During the PhD of Guillaume Duceux [5], we developed a multi-modal approach integrating lidar and visual data to detect changes in the environment and discover objects in an unsupervised fashion from these changes [85]. During the PhD of Louis-Charles Caron [3] and the post-doc of Panagiotis Papadakis, we developed several approaches for object recognition and semantic mapping using color and depth cameras [71, 70, 109], we focused in particular on different ways of fusing these two types of information to improve the robustness in real-world applications, beyond the tests on image databases. During the PhD of Alexandre Armand [1] in collaboration with Renault, we also studied how Gaussian Processes [62] and ontologies [64] can be used to improve environment analysis for a car in order to better anticipate dangerous situations.

Positioning: Our approaches to learn concept and features from data acquired by exploration or during interaction with a human are directly related to the large amount of deep learning approaches to representation learning. However, we focused mainly on the conditions that can make learning possible and efficient on a robot (by using intrinsically motivated exploration, incremental learning or multi-modal and unsupervised learning) and as such are complementary of the research in deep-learning for vision led in other labs.

2.8.1 Collaborations

Olivier Sigaud and Stéphane Doncieux, Robotics research institute (ISIR), Univ. Pierre et Marie Curie, France: we collaborated within the ANR MACSi, and the H2020 DREAM projects.

Uwe Handmann and Stefan Geisler, university of applied sciences of Bottrop (Germany): we collaborated on the subject of multimodal hand gesture recognition, co-supervising the PhD of Thomas Kopinski.

Javier-Ibanez Guzman, Renault S.A.S. : we collaborated on the application of machine learning to driver assistance with the PhD of Alexandre Armand

Jean-Francois Goudou, Thales : we collaborated on the application of intrinsic motivation for visual saliency learning with the PhD of Celine Craye

External support

We had support from the ANR MACSi projet (PhD of Natalia Lyubova), the H2020 DREAM project (PhD of Clement Masson), the PSPC ROMEO2 project (Post-Doc of Panagiotis Papadakis), a contract from Honda Research Institute USA Inc (Post-Doc of Michael Garcia-Ortiz), a PhD grant from CRSNG (Canada) for Louis-Charles Caron, from DGA (Guillaume Duceux) and from Ecole Polytechnique (Adrien Matricon and Thomas Hecht). We had two CIFRE PhD grants with Renault (Alexandre Armand) and Thales (Celine Craye).

2.9 Research axis 6: Educational technologies: Leveraging models of curiosity-driven active learning and teaching

Personnel

Benjamin Clement, Alexandra Delmas, Pierre-Yves Oudeyer, Didier Roy, Manuel Lopes

Scientific achievements and positioning

Kidlearn is a research project studying how machine learning models of intrinsically motivated active learning (see previous sections) can be applied to intelligent tutoring systems. It aims at developing methodologies and software which adaptively personalize sequences of learning activities to the particularities of each individual student. Our systems aim at proposing to the student the right activity at the right time, maximizing concurrently his learning progress and its motivation. In addition to contributing to the efficiency of learning and motivation, the approach is also made to reduce the time needed to design ITS systems.

We presented an approach to Intelligent Tutoring Systems which adaptively personalizes sequences of learning activities to maximize skills acquired by students, taking into account the limited time and motivational resources (this personalization approach is mathematically equivalent to algorithms developped in Research Axis 1 which automatically generate learning curricula for autonomous robots). At a given point in time, the system proposes to the students the activity which makes them progress faster. We introduced two algorithms that rely on the empirical estimation of the learning progress, **RiARiT** that uses information about the difficulty of each exercise and **ZPDES** that uses much less knowledge about the problem.

The system is based on the combination of three approaches. First, it leverages recent models of intrinsically motivated learning by transposing them to active teaching, relying on empirical estimation of learning progress provided by specific activities to particular students. Second, it uses state-of-the-art Multi-Arm Bandit (MAB) techniques to efficiently manage the exploration/exploitation challenge of this optimization process. Third, it leverages expert knowledge to constrain and bootstrap initial exploration of the MAB, while requiring only coarse guidance information of the expert and allowing the system to deal with didactic gaps in its knowledge. The system is evaluated in a scenario where 7-8 year old schoolchildren learn how to decompose numbers while manipulating money. Systematic experiments are presented with simulated students, followed by results of a user study across a population of 400 school children [77, 78, 75, 76, 21, 170].

A Comparison of Automatic Teaching Strategies for Heterogeneous Student Populations Online planning of good teaching sequences has the potential to provide a truly personalized teaching experience with a huge impact on the motivation and learning of students. In this work we compare two main approaches to achieve such a goal, POMDPs that can find an optimal long-term path, and Multi-armed bandits that optimize policies locally and greedily but that are computationally more efficient while requiring a simpler learner model. Even with the availability of data from several tutoring systems, it is never possible to have a highly accurate student model or one that is

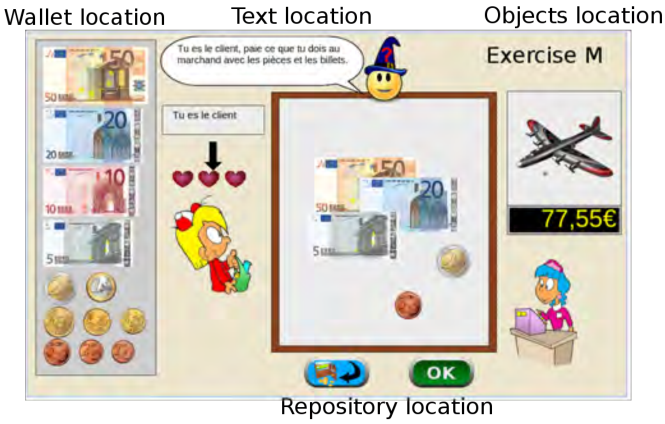


Figure 3: Graphical interface used in the Kidlearn project.

tuned for each particular student. We studied what is the impact of the quality of the student model on the final results obtained with the two algorithms. Our hypothesis is that the higher flexibility of multi-armed bandits in terms of the complexity and precision of the student model will compensate for the lack of longer term planning featured in POMDPs. We presented several simulated results showing the limits and robustness of each approach and a comparison of heterogeneous populations of students. This work has been publish and presented at Educational Data Mining 2016 conference in Raleigh, USA [75].

Software The code for reproducing these algorithms and experiments is available as open-source on Github: `https://github.com/flowersteam/kidlearn/`

The KidBreath project To create learning contents linked to asthma to personalize it like mathematics activities in Kidlearn project [21] we used recommandation criterias in Therapeutic Education Program for asthma kids made by Health High Autority. Following an approach of participatory design [BVO$^+$10], contents were validated by medical experts like health educators, pulmonoligists and pediatrics. Then, we conducted a workshop with forty kids aged 8 in order to iterate over the application interfaces and evaluate enjoy about it with observations. Finally, we realized a focus group with 5 asthma kids to validate the global comprehension of a part of the content. It revealed that children wanted more contents about the crisis treatment and how the asthma works in the human system (verbatims).

In a preliminary study, we experimented two conditions in 20 control children (with 3 asthma kids), one giving the possibility of choosing activities like the child wants, and one no giving this choice (activities displayed in random). No significative difference between the two groups, but results showed KidBreath was easy to use with scores > 75 using System Usability Scale [B$^+$96]. Based on Cordova and Lepper works to evaluate motivation and knowledge with similar system and population [CL96], children had their disease knowledge increased with just one week use and were motivated using it. Finally, asthma kids showed they were more engaged than healthy kids and used KidBreath more seriously (stayed in breaks). These results were presented in the 5th edition of Serious Games in Medicine Conference in Nice.

2.9.1 Impact and collaborations

The work on intelligent tutoring systems is being very impactful, and benefits from collaborations of key actors in the domain of Intelligent Tutoring Systems for its dissemination. It is the first time that such a strong personalization is being tried. In addition, the large scale experiment conducted with 400 children in primary schools is a major experimental achievement. Several companies are interested in using these mechanisms, and two of them have began to include them in their products (ITWell). The project was always run in collaboration with primary school and the educational system of the region. This allowed to simultaneously show our research and also to run the experiments.

External support

This project is being partially financed by the KidLearn project of Conseil Regional d'Aquitaine.

3 Knowledge dissemination

3.1 Publications

	year1	year2	year3	year4	total
PhD Theses	3	3	4	1	11
H.D.R. (*)	0	1	0	1	2
Journals	13	6	12	12	43
Conference proceedings (**)	26	35	23	18	102
Book chapters	3	0	0	0	3
Books (written)	0	0	1	0	1

(*) HDR Habilitation à diriger des Recherches
(**) Conferences with a program committee

Major journals in cognitive developmental robotics and artificial intelligence:
- IEEE Transactions on Autonomous Mental Development (TAMD) : 3
- IEEE CDS Newsletter on Cognitive and Developmental Systems : 8
- IEEE Transactions on Robotics : 1
- Neural Networks : 1
- IEEE Transactions on Neural Networks and Learning Systems : 1
- Autonomous Robots : 2
- Frontiers in Neurorobotics : 1
- Journal of Educational Data Mining (JEDM) : 1
- International Journal of Social Robotics : 1
- Robotics and Autonomous Systems : 2
- PLoS ONE : 3

Major journals in cognitive sciences:
- Trends in Cognitive Sciences : 1
- Vision Research : 1
- Journal of Phonetics : 3
- Topics in Cognitive Science : 1
- Frontiers in Neuroscience : 1
- Frontiers in Psychology : 2
- Scientific Reports : 1
- Behavioral and Brain Sciences : 1
- Progress in Brain Research : 1

Major conferences:
- The fourth joint IEEE International Conference on Development and Learning and on Epigenetic Robotics (ICDL-Epirob) : 23
- IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS) : 12
- International Conference on Robotics and Automation (ICRA) : 3
- International Joint Conferences on Artificial Intelligence (IJCAI) : 2
- Conference on Uncertainty in Artificial Intelligence (UAI) : 1
- Twenty-Eighth AAAI Conference on Artificial Intelligence (AAAI) : 1
- European Symposium on Artificial Neural Networks, Computational Intelligence and Machine Learning (ESANN) : 8
- International Conference on Artificial Neural Networks (ICANN) : 4
- International Joint Conference on Neural Networks (IJCNN) : 3
- IEEE-RAS International Conference on Humanoid Robots (IJCNN) : 4
- International Conference on Educational Data Mining (EDM) : 2
- International Conference on Machine Learning (ICML) : 2

- International Conference on Autonomous Agents and Multiagent Systems, (AAMAS) : 1
- Annual Conference of the Cognitive Science Society (CogSci) : 1
- International Conference on the Evolution of Language (EVOLANG) : 1

3.2 Visibility

3.2.1 Awards

- Sébastien Forestier, Yoan Mollard, Damien Caselli and Pierre-Yves Oudeyer obtained the **2nd place for the demonstration award at NIPS 2016** conference for their demonstration on Autonomous exploration, active learning and human guidance with open-source Poppy humanoid robot platform and Explauto library https://hal.inria.fr/hal-01404399/document
- PY. Oudeyer was awarded the **Lifetime Achievement Award** from the Evolutionary Linguistics Association.
- **Best Paper Award, IEEE Transactions on Robotics** In April 2013 at the International Conference on Robotics and Automation in Karlsruhe, Freek Stulp received the "King-Sun Fu Best Paper Award of the IEEE Transactions on Robotics". As T-RO has on of the highest impact factors, this is considered to be the highest paper prize in robotics. It is the first time this prize has been awarded to an article on machine learning.
- Didier Roy was award the **prize Serge Hocquenguem** for his work on educational robotics, http://psh.aid-creem.org/spip.php?rubrique1 and http://binaire.blog.lemonde.fr/2016/12/09/pourquoi-didier-et-eva-jouent-avec-le-meme-robot/
- **Best PhD thesis (Prix Le Monde):** Jonathan Grizou obtained the "Prix Le Monde de la recherche universitaire" for his thesis and work on "Learning from unlabeled interaction". This work allowed in particular to develop new algorithms for Brain-Computer Interfaces that remove the need for a phase of calibration and allow users to achieve sequential tasks. This work was achieved in collaboration with I. Iturrate and L. Montesano (Univ. Zaragoza, Spain), and the PhD was co-supervised by M. Lopes and PY. Oudeyer.
- **2nd Best PhD thesis (GdR Robotique):** Matthieu Lapeyre obtained the "Second prix de thèse du GDR Robotique" for his thesis on the development of the open-source 3D printed Poppy Humanoid platform, now in use in various scientific, educational and artistic projects worldwide http://www.poppy-project.org . This work was achieved in collaboration with P. Rouanet and the PhD was supervised by PY Oudeyer.
- **Global Fab Award finalist (Fab 10)** Poppy Project was finalist at international conference Fab 10 in 2014.
- **Best PhD thesis (Région Aquitaine):** Thomas Cederborgs PhD thesis "A Formal Approach to Social Learning: Exploring Language Acquisition Through Imitation" won the "TheSAqt" prize, awarded by Region Aquitaine who gives this awards to excellent theses in the region.
- **Best PhD thesis poster (Univ. Bordeaux):** O. Mangin obtained the Best thesis poster from Bordeaux doctoral school of mathematics and computer science, for his PhD thesis "The Emergence of Multimodal Concepts: From Perceptual Motion Primitives to Grounded Acoustic Words".

3.2.2 Leadership within the Scientific Community

We have played an important role in the growth and structuring of the new scientific field "Developmental Robotics" at both the national and international levels, with several aims:

- To help building a strong unified and integrated scientific identity of the field, and a good positioning relative to connected fields (especially relative to Robotics, and in particular Robot Learning and Human-Robot Interaction on the one hand, and Cognitive Sciences/Developmental Psychology/Neuroscience/Linguistics on the other hand);
- To develop tools for focused, efficient and impactful scientific interactions in the community (conferences, journals,newsletters);
- To gather and train young scientists to become competent in this field, requiring pluridisciplinar integration and formation;

This role is attested by the activities described below.

3.2.3 Chair in international organizations and steering committees

- 2015-2016: PY Oudeyer has been **Chair of IEEE Computational Intelligence Society technical committee on cognitive and developmental systems** (10 task forces, 65 members); The activities of the TC take a lead role for the development of the cognitive and developmental systems field. They are described at https://openlab-flowers.inria.fr/t/ieee-cis-tc-on-cognitive-and-developmental-systems/41.
- 2008-2015: Member of the steering committee of the IEEE ICDL-Epirob conference
- 2014-2015: Member of the steering committee of the fOSSa conference
- 2006-2014: Member of the IEEE CIS Technical Committee on Autonomous Mental Development (now named TC committee on cognitive and developmental systems).

3.2.4 Scientific Events Organisation

General Chair, Scientific Chair

- PY Oudeyer and Manuel Lopes have been general chair of First interdisciplinary symposium on Information-seeking, curiosity and attention, Bordeaux, 2014 and general co-chair of Second Interdisciplinary Symposium on Information Seeking, Curiosity and Attention (Neurocuriosity), London, 2016 (150 participants, https://openlab-flowers.inria.fr/t/second-interdisciplinary-symposium-on-information-seeking-curiosity-and-attention-neurocuriosity-2016/187
- D Roy has organized and been general chair of Colloque Robotique et Education: Research, users reports, talks and workshops about robotics for education, Bordeaux, 2015 and has been general chair of the colloquium ”Robotique et Education” in Bordeaux, 2016.

Member of the Organizing Committees

- PY Oudeyer has been member of the steering committee of the IEEE ICDL-Epirob 2015 & 2016 and fOSSa 2015 & 2016 conferences, ”Robotics Liaison” of IJCNN 2017, Anchorage, and workshop chair of the IJCNN 2015 International Joint Conference on Neural Networks, Killarney 2015.
- Manuel Lopes has co-organized the R:SS workshop on Bootstrapping Manipulation Skills 2016.
- Alexander Gepperth has co-organized a special session (”Incremental learning algorithms and application”) on ESANN, together with Barbara Hammer of Bielefled university (Germany) 2016.

3.2.5 Scientific Events Selection

Member of the Conference Program Committees

- PY Oudeyer has been member of the program committee of IEEE ICDL-Epirob 2013, 2014, 2015 & 2016, as well as of Humanoids, IROS, ICRA 2013.

- Manuel Lopes has been member of the conference committee for HRI, AAMAS 2015.
- David Filliat has been member of the evaluation committee for the ANR Apprentissages program and member of the program committee for the REACTS workshop 2013 and member of the conference committee for ECMR 2015.
- Clément Moulin-Frier has been program chair at the ICDL-Epirob conference to be held at Brown University, Providence, Rhode Island 2014.
- Freek Stulp has been on the program committee of ICRA 2013 and RSS 2014.
- Alexander Gepperth has been on the programme committee of ESANN 2014, IJCNN 2013, 2014 & 2016, ECAI 2016, and ESANN 2016.

3.2.6 Journal

Member of the Editorial Boards

- PY Oudeyer has been editor of IEEE CIS Newsletter on Cognitive and Developmental Systems: twice a year he entirely organizes a scientific debate (dialog) by soliciting a well-known researcher on a specific topic, then inviting other key researchers (typically 6-10) to respond and editing and coordinating their contributions. This newsletter is the main electronic communication channel in the developmental robotics community, and also impacts the developmental sciences at large across psychology, neuroscience and artificial intelligence. It is distributed to a dedicated mailing list counting around 1700 subscribers (as well as to other major mailing lists): https://openlab-flowers.inria.fr/t/ieee-cis-newsletter-on-cognitive-and-developmental-systems/129
- PY Oudeyer has been member of editorial board for journals IEEE CDS/TAMD, International Journal of Social Robotics, Frontiers in Neurorobotics, Frontiers in Humanoid Robotics, and IEEE RAS Letters. He has also been on the editorial board of Advances in Interaction Studies, John Benjamins Publishing Company. He also guest edited a special issue of the Journal of Phonetics, on the cognitive nature of speech sounds (with Clément Moulin-Frier) 2015.
- Manuel Lopes has been member of the steering committee of the IEEE RAS TC on Robot Learning 2013 and associated editor for the, IEEE Transactions on Autonomous Mental Development 2015.
- David Filliat has been Associate Editor for IROS 2013, 2014, 2015 & 2016 and member of the conference committee for ECMR 2015.
- Freek Stulp has been an Associate Editor for IROS and ICRA 2014.

3.2.7 Reviewing

Conference reviewing:

- PY Oudeyer has been a reviewer for IROS 2015, ICRA 2015, IEEE ICDL-EPIROB 2015 & 2016, and Humanoids 2016.
- Manuel Lopes has been reviewer for IROS 2014-2016, ICRA 2014-2016, HRI 2014, AAMAS 2014, IJCAI 2015 & 2016, NIPS 2016, and IEEE ICDL-EPIROB 2016.
- David Filliat has been reviewer for the conferences ECMR 2013, ICRA 2013, 2014 & 2016, IROS 2013 & 2014, IV 2013 & 2016, ICARCV 2014, RFIA 2014-2016, ESANN 2015, ECMR 2015, IFAC 2016.
- Alexander Gepperth has been reviewer for IROS 2013 & 2014, ITSC 2013 & 2014, IJCNN 2013, 2014 & 2016, ESANN 2014 & 2016, IV 2016, and ECAI 2016.
- Jonathan Grizou has been reviewer for ICDL-Epirob 2013, Robotica 2013, ICDL 2014, and HRI 2014.
- Freek Stulp has been reviewer for the conferences IJCNN 2013, IROS 2013 & 2014, ICRA 2013 & 2014 , IEEE Humanoids 2013.

- Sébastien Forestier has been reviewer for IEEE ICDL-Epirob 2016.
- Thibaut Munzer has been reviewer for IROS 2015 and IEEE IJCAI 2016.
- Baptiste Busch has been reviewer for IEEE RO-MAN 2016.
- Pierre Rouanet has been reviewer for IROS 2015.
- Clément Moulin-Frier has been reviewer for the ICDL-Epirob conference 2013.

Journal reviewing

- PY Oudeyer has been reviewer for journals Proceedings of IEEE 2013, Topics in Cognitive Science 2013, Frontiers in Psychology 2013, IEEE ICDL-Epirob 2014, ICRA 2014, IEEE TAMD 2014 & 2015, Infancy 2015, Journal of Infant Behavioral Development 2015, Journal of Phonetics 2015, Robotics and Automation Magazine 2016, the Journal of Language Evolution 2016.
- Manuel Lopes was reviewer for IEEE Transactions on Robotics, IEEE Transactions on Autonomous Mental Development 2014.
- David Filliat has been reviewer for the Autonomous Robots journal 2013, International Journal of Robotics Research 2014-2016, Robotics and Autonomous Systems 2014, Neurocomputing 2014, IEEE Transaction on Robotics 2015.
- Alexander Gepperth has been reviewer for Cognitive Computation 2013, Transactions on Intelligent Transportation systems 2013, 2014 & 2016, Neurocomputing 2013 & 2014, Neural Networks and Neural Processing Letters 2013 & 2014.
- Anna-Lisa Vollmer has been reviewer for Frontiers in Robotics and AI 2015 & 2016, Transactions on Autonomous Mental Development 2015, and IEEE Transactions on Cognitive and Developmental Systems 2016.
- Pierre Rouanet has been reviewer for IEEE Transactions on Human-Machine Systems 2014 and IEEE Robotics and Automation Letters 2015.
- Freek Stulp has been reviewer for journals IEEE Transactions on Robotics, Autonomous Robots 2013 & 2014, IEEE Transactions on Autonomous Mental Development 2013, and Journal of Intelligent and Robotic Systems 2013.
- Jonathan Grizou has been reviewer for IEEE Transactions on Autonomous Mental Development 2014.
- Clément Moulin-Frier has been reviewer for the IEEE Transactions on Autonomous Mental Development journal 2013.

3.2.8 Scientific Expertise

- PY Oudeyer has been expert for the European Commission, expert for the OPECST office at Assemblée Nationale, about the role and evolution of robotics within society, 2015, expert for the EU Commission scientific programme, 2015 & 2016, expert for Académie des Technologies and OPECST on artificial intelligence and its interaction with society, 2016, expert for Main à la Pâte for the textbook project "1, 2, 3: Codez!" to teach computer science in primary schools, 2016, expert for the Polish National Research Agency 2016, and for the Swedish National Research Agency, 2016, has been expert for the Cherry Project, IPB, Bordeaux, 2015.
- Manuel Lopes has been expert for the EU Commission scientific programme, 2016.

3.2.9 Research Administration

PY Oudeyer has been scientific responsible of Inria-Ensta-ParisTech EPC (35 members in jan. 2016).

3.2.10 Invited Talks

- PY Oudeyer, ”How robotic modelling can help us understand complex dynamics in development”, keynote (Views by two) at the International Conference on Infant Studies, New-Orleans, 2016.
- PY Oudeyer, ”Robotique éducative: les projets de l'équipe Flowers”, Colloque Robotique et Education, 2016.
- PY Oudeyer, ”Curiosity, exploration and learning in humans and machines”, ISSAS Summer School, Geneva, 2016.
- PY Oudeyer, ”How robotic modelling can help us understand complex dynamics in language and sensorimotor development”, Creativity and Evolution Summer School, Como, 2016.
- PY Oudeyer, ”Comment la modélisation robotique aide à comprendre la dynamique du développement de l'enfant”, Colloque Biologie et Information, Cerisy, 2016.
- PY Oudeyer, ”Active exploration for lifelong developmental learning in humans and machines: intrinsic motivation, maturation and social guidance”, Google Deepmind, London, 2016.
- PY Oudeyer, ”Diverstiy of forms and developmental functions of curiosity-driven exploration”, London, 2016.
- PY Oudeyer, ”Intelligence artificielle et humain”, Entretiens de la Cité, Lyon, 2016.
- PY Oudeyer, ”Artificial intelligence and robotics: scientific, technological and societal challanges”, Académie des Technologies, Paris, 2016.
- PY Oudeyer, ”From fundamental research in models of human learning to educational applications”, Journée Learning Lab, Paris, 2016.
- PY Oudeyer, ”Diverstiy of forms and developmental functions of curiosity-driven exploration”, Journée GdR Robotique et Neuroscience, Bordeaux, 2016.
- David Filliat, “Apprentissage pour les vehicules intelligents et la robotique developpementale” during the workshop “Intelligence Artificielle et Véhicule à Conduite Deleguee” organized by VEDECOM 2016.
- PY Oudeyer, ”Open-source art/science with Poppy Project”, Journée ECARTS, Univ. Bordeaux 2016.
- PY Oudeyer, ”Mondes Mosaiques”, Librairie Mollat, Bordeaux, 2016.
- PY Oudeyer, ”Self-organization and active learning of language”, Lattice, ENS Paris, 2016.
- PY Oudeyer, ”Intelligence artificielle et robotique”, Grand Palais, Paris, 2016.
- PY Oudeyer, ”Intelligence artificielle et philosophie”, Bordeaux, 2016.
- PY Oudeyer, ”Machine learning and robotics”, Technion ConnectedWorld conference, Paris, 2016.
- PY Oudeyer, “Open-source baby robots for science, education and art”, Evostar 2015 international conference on bio-inspired computation, 2015.
- PY Oudeyer, “Building open-source robots capable of autonomous learning”, Devoxx 2015 international conference, 2015.
- PY Oudeyer, “Developmental robotics and open-ended learning”, BICA 2015 international conference on Biologically Inspired Cognitive Architecture, 2015.
- PY Oudeyer gave a Spotligh talk at the OEB 2015 international conference on technology supported learning and training, 2015.
- PY Oudeyer, “Open-source baby robots: modelling sensorimotor development with robots”, “Journée Brain”, Univ. Bordeaux, 2015.
- PY Oudeyer, “Poppy: Open-sour ce educational robot platform”, Colloque GEII, 2015.
- PY Oudeyer, “Modélisation robotique du développement cognitif', sensoritmoteur et social”, CogTalk, Zig Zag bar/Association of cognitive science students of Univ. Bordeaux,

2015.

- PY Oudeyer, “Robotique développementale et sociale”, Workshop Interactions Homme-Robots dans le contexte d’applications culturelles, La Rochelle, 2015.
- PY Oudeyer, “Online optimization and personalization of teaching sequences: from developmental robotics to e-learning”, International Teacher’s Cognition workshop, Ecole Normale Supérieure, Paris, 2015.
- PY Oudeyer, “Auto-organisation et curiosité dans le développement et l’évolution du langage”, Séminaire du laboratoire du LATTICE, Ecole Normale Supérieure de Paris, 2015.
- PY Oudeyer, “Histoire et enjeux éducatifs de l’intelligence artificielle et de la robotique”, dialog with JG Ganascia and M Doueihi at the Artificial Intelligence and Society seminar at College des Bernardins, Paris, 2015.
- Freek Stulp, ”Robot Skill Learning: Back to the Future”, Josef Stefan Institute, Ljubljana, 2015.
- Freek Stulp, ”Many regression algorithms, one unified model - A tutorial”, Josef Stefan Institute, Ljubljana, 2015.
- Anna-Lisa Vollmer, ”Teaching, a bidirectional process: Evidence from adult-child and human-robot interaction”, Tenth International School on Mind, Brain and Education, Ettore Majorana Foundation, Erice, 2015.
- Manuel Lopes, ”Interactive Learning for Cooperative Human-Robot Tasks”, Algorithms for Human Robot Interaction Workshop, University of Berkeley, 2015.
- Manuel Lopes, ”Exploration Biases for Task Learning In Machines and Animals”, Redwood Center for Theoretical Neuroscience, 2015.
- William Schueller, ”Active Learning and Active Control of Complexity Growth in Naming Games”, Complexity & Quantitative Linguistics Lab, Universitat Politècnica de Catalunya, Barcelona, 2015.
- Didier Roy, Stéphanie Noirpoudre, Thibault Desprez, ”Boussoles du numérique” 2015.
- Didier Roy, Pierre-Yves Oudeyer, ”Assises nationales de la médiation numérique”, 2015.
- Didier Roy, ”Escales de l’éducation (ligue de l’enseignement)”, 2015.
- Didier Roy, ”Symposium Scratch Amsterdam: presentation of Snap! programming”, 2015.
- Didier Roy gave several talks at Cap Sciences, 2015.
- Didier Roy, ”Forum EIDOS 64 Pau : talks about educational robotics” 2015.
- Manuel Lopes made a plenary talk at the conference Technologies de l’Information et de la Communication pour l’Enseignement (TICE), Beziers, 2014.
- Manuel Lopes made an invited talk at the Robotics: Science and Systems : Workshop on Learning Plans with Context From Human Signals, USA, 2014.
- Manuel Lopes made an invited talk ICRA Workshop on Active Visual Learning and Hierarchical Visual Representations for General-Purpose Robot Vision, Hong-Kong, 2014.
- Manuel Lopes made an invited talk ICRA Workshop on Autonomous Grasping and Manipulation: An Open Challenge, Hong-Kong, 2014.
- Alexander Gepperth gave an invited lecture at the FP7-sponsored Summer School ”Neuronal dynamics approaches to cognitive robotics”, Bochum, 2014.
- Matthieu Lapeyre gave a talk at Journéees Scientifiques Inria about the Poppy project and especially on the open source aspects of the project, 2014.
- Matthieu Lapeyre participated to Open experience at WAVE conference about new models of distribution and presented the particularity of Poppy as an open science project, 2014.
- Matthieu Lapeyre made a talk at Digital Intelligence conference held in Nantes (France) about the use of Poppy for educational and artistic applications, 2014.
- Olivier Mangin made an invited talk at Language and Body symposium, International Association for the Study of Child Language Conference (IASCL), Amsterdam, 2014.
- Steve N’Guyen gave a talk at the ISIR lab (Institut des Systèmes Intelligents de et Robotique,

Paris) about the Poppy project, 2014.

- Clément Moulin-Frier gave two invited talks. The first one was at the Humanoids conference in Madrid, during the workshop entitled Active Learning in Robotics: Exploration Strategies in Complex Environments. The second one was at the PyconFr, a French software developer conference2014.
- PY Oudeyer, “Developmental Robotics: Lifelong Learning and the Morphogenesis of Developmental Structures”, AAAI Spring Symposium on Implementing Selves with Safe Motivational Systems and Self-Improvement, Stanford Univ., 2014.
- PY Oudeyer, “Curiosity-driven learning and development: How robots can help us understand humans”, WACAI, 2014.
- PY Oudeyer, “Emergence du langage et robotique développementale”, Séminaire de l’association X-SHS, 2014.
- PY Oudeyer, “Developmental Robotics: Lifelong Learning and the Morphogenesis of Developmental Structures”, Dagstuhl Seminar 14081 on ”Robots learning from experiences”, 2014.
- PY Oudeyer, “La robotique comme outil pour comprendre les origines du langage”, Rencontres Mollat, Bordeaux, 2014.
- PY Oudeyer, “Comment les robots nous aident a comprendre l’homme”, Forum des Sciences Cognitives, Paris, 2014.
- PY Oudeyer, “Fabricating Open-Source Baby Robots”, Tedx Cannes, 2014.
- PY Oudeyer, “Poppy: Open Source Robotics Platform for Science, Art and Education”, La Cantine, Rennes, 2014.
- PY Oudeyer, “Open Source Developmental Robotics”, Bodywara workshop Inria/FING, Bordeaux, 2014.
- PY Oudeyer, “KidLearn: Machine learning for personalizing educational contents”, Digital Intelligence conference, Nantes, 2014.
- PY Oudeyer, “The roles of active learning in sensorimotor and language development”, International Conference of of the International Society of Infant Studies (ISIS 2014), Symposium on Integrative models of language acquisition, 2014.
- PY Oudeyer, “Curiosity-driven learning and development in robots”, IX Advanced Multimodal Information Retrieval int’l summer school, 2014.
- PY Oudeyer, “Open source developmental robotics”, Séminaire du Centre de Recherche Interdisciplinaire, Univ. Paris VII, 2014.
- PY Oudeyer, “The impact of curiosity-driven learning on self-organization of developmental process: robotic models”, First International Symposium on Information Seeking, Curiosity and Attention, Bordeaux, 2014.
- PY Oudeyer, “Modeling cognitive development with robots”, Seminar of the Center for Brain and Cognitive Development, Birbeck college, 2014.

3.3 Technology transfer and socio-economic impact

Socio-economic impact is an essential component of the team’s work. As such, most scientific and technological projects have dimensions of socio-economic impact which we have described in other sections (so please refer to these sections for details). In particular:

Societal impact:

- Design and dissemination of educational technologies and educational content for the education of computer science at all levels of schools (from primary schools to high-school and post-bac), with the projects Inirobot (included in the textbook “1,2,3 codez” from Main à la pate, this educational robotics kit is already used by $>$ 15000 children in France and in other French speaking countries); and Poppy Education (educational robotic kits used in several dozens colleges and high-schools, also used as tools to promote computer science education in interventions at Assemblée Nationale and Sénat). Web: https://dm1r.fr and http://www.poppy-education.org.

- Popular science activities through writing of wide audience books, participating in high frequentation exhibition related to science, and regular intervention in the media to explain various dimensions of scientific developments in robotics, artificial intelligence and cognitive sciences. See the "Outreach" section and at: (http://www.pyoudeyer.com/popular-science/).

Selected industrial transfers:

- 2016: **The Pollen Robotics company was created as a spin-off of the Flowers team**, and in particular as a spin-off of the Poppy project: http://www.pollen-robotics.com. The company has currently 3 operational people and benefited from funding from Region Aquitaine and Inria.
- 2015-16: In order to foster and at the same time control the dissemination of the open-source Poppy robotic platforms (Poppy Humanoid, Poppy Torso, Poppy ErgoJr), the trademark "Poppy" was protected internationally in more than 8 countries. **A contract for commercialization and distribution of Poppy educational robotics kit was made between Inria and Generation Robots company**, and the kits are now commercially available: https://www.generationrobots.com/en/279-poppy-opensource-robotics-platform.
- 2015-2016: In addition to schools and universities, some major companies are also now using the Poppy platform for educational purposes, e.g. Dassault System, the company that makes and sells the SolidWorks and Catia software (leading software in CAD design), use Poppy as a central platform in their educational training programs https://academy.3ds.com/en/lab/poppy-humanoid-robot-and-3dexperience
- 2015-16: The algorithms for personalization of pedagogical activities in the KidLearn and KidBreath projects have been reused directly in products beind developped by several companies: the ITWell e-health company is including them in a software application for kids with chronic diseases (e.g. astham);

3.4 Outreach (general audience action)

3.4.1 Inirobot: A large scale educational robotics outreach project for primary schools

IniRobot (a project done in collaboration with EPFL/Mobsya) aims to create, evaluate and disseminate a pedagogical kit which uses Thymio robot, open-source and low cost, for teaching computer science and robotics. We developped and disseminated/deployed the IniRobot pedagogical kit, for the discovery of computer science and robotics in primary schools (school children aged from 7 to 10 years old). This was done thanks to the recruitment in the team of Didier Roy, a math teacher (college) and specialist of ICT in education. IniRobot provides a microworld for learning, and takes an enquiry-based educational approach, where kids are led to construct their understanding through practicing an active investigation methodology within teams. The kit was first developed and evaluated in primary schools in Gironde (during the activities of Temps d'accueil périscolaire), in collaboration with a group of teachers. Then, it was deployed to a large scale in France and abroad (see below). A dedicated web site has been created, allowing all users and contributors to access the kit (Creative Commons) and share their experiences (https://dm1r.fr). Example of action in university: MEEF teacher training for the hope of Aquitaine. Example of action in school: training of all Gironde Pedagogical ICT Advisors, covering nearly 1000 schools. Example of action in the extracurricular time: training 82 facilitators TAP cities of Talence, Pessac, Lille, ..., CDC Gates of inter-seas. Example of national action: Training of the digital mediators of the 8 Inria centers.

Impact: The kit is free of use (under Creative Commons CC-BY-SA licence) and now used by **more than 15000 children in France, with around 1400 adults educators/teachers, covering more than 1000 primary schools in 54 towns, in France and Switzerland** (e.g. Talence, Lille, Lormont, Bruges, Mérignac, Floirac, Pessac, Quinsac, Cenac, etc). This scaling up has been achieved through collaboration with the national official educational structures (Rectorats) as well as the Canope network, with the organization of systematic training of teachers of educators, supported by projects such as the eFran project "Perseverons". An adaptation of the kit has been included in the education book "1, 2, 3 codez" for the initiation to computer sciences and in preparation by Main à la Pate foundation, to which we have directly contributed as scientific consultants and co-authored of several parts (http://www.fondation-lamap.org/fr/123codez). This educational book has been disseminated to more than 8000 primary school teachers in France.

Created pedagogical documents and resources

- IniRobot pedagogical kit [174]: This pedagogical booklet provides activities scenarized as missions to do. A second pedagogical booklet has been also created by three pedagogical advisers for primary school, with pedagogical instructions and aims, under ou supervision. http://tice33.ac-bordeaux.fr/Ecolien/ASTEP/tabid/5953/language/fr-FR/Default.aspx A new pedagogical kit is in progress, Inirobot Scratch, which will propose activities with Scratch and Snap! and Thymio robot.
- Inirobot website and forum https://dm1r.inria.fr/inirobot or http://www.inirobot.fr With this website, teachers, animators and general public can download documents, exchange about their use of inirobot' kit.
- Publication about Inirobot and Poppy Education A poster and talk were produced in Didapro-Didastic 6 Conference in Namur (Belgium) on 2016 January. [184]

3.4.2 Poppy Education project

We are coordinating the Poppy Education project which aims to create, evaluate and disseminate complete pedagogical kits "turnkey solutions" (with Creative Commons licences), open-source and low cost, for teaching computer science and robotics lhttps://www.poppy-project.org/education/?lang=fr). It is designed to help young people to take ownership with concepts and technologies of the digital world, and provide the tools they need to allow them to become actors of this world, with a considerable socio-economic potential. It is carried out in collaboration with teachers and several official french structures (French National Education, Highschools, engineers schools, ...). For secondary education and higher education, scientific literacy centers, Fablabs. The Poppy robotic platform used in the project is free hardware and software, printed in 3D, and is intended primarily for:

- learning of computer science and robotics
- introduction to digital manufacturing (3D printing ...)
- initiation to the integration of IT in physical objects in humanoid robotics, mechatronics
- artistic activities

Educational sectors covered by the project are mainly STEMs disciplines in highschools.

In the context of the projects Inirobot and Poppy Education, we have organized two large conferences on "Robotics and education" in 2014 and 2015 (150 participants) in Bordeaux: http://dm1r.fr/colloque-robotique-education/. All conference videos are available on the web : https://www.youtube.com/watch?v=prFmC-BpdY8&index=1&list=PL9T8000j7sJBC_H3L_hS-i4Ltlh1Fz2FY. This has allowed us to play a central role in getting the Scratch International Conference organized in Bordeaux in 2017, where we are part of the organizing committee (http://www.scratch2017bdx.org/en/hello-world-2/).

We participated to many events and workshops for the general public, e.g. in 2016: : Colloque Didapro-Didastic Namur janvier 2016 , EIDOS janvier 2016, Robot's Makers Day ENSEIRB

Cluster Aquitaine Robotics janvier 2016, Educatec-Educatice mars 2016, Journées numériques ESPE Aquitaine mars 2016, Journées robotique et éducation IFE Lyon mai 2016, Bordeaux Geek Festival mai 2016, Forum des Nouvelles Initiatives de Médiation Scientifique NIMS CPU CNRS mai 2016, Université d'été Ludovia août 2016.

The educational robotic kits developped first began to be used in Region Aquitaine (¿ 15 highschools, see below), and they are now being integrated into larger scale programs such as the national Class Code educational project for introducing computer science at all levels at school (target is to train ¿ 300 000 school children to computer science), and in several international projects in the Carribean and in Africa.

Pedagogical experimentations : Design and experiment robots and the pedagogical activities in classroom Users and their needs are placed at the center of this project. The pedagogical tools of the project are being created directly with them and evaluated in real life by experiments. Experimentations have began to be setup in 10 high-schools of Region Aquitaine, and 3 university level institutions: Lycée Camille Jullian (Bordeaux), Lycée Victor Louis (Talence), Lycée Saint Genès (Talence), Lycée François Mauriac (Bordeaux), Lycée Jean Moulin (Langon), Lycée des Graves (Gradignan), Lycée Sud Medoc (Le Taillan Medoc), Lycée Alfred Kastler (Talence), Lycée Raoul Follereau (Nevers), Aérocampus Auqitaine, ENSEIRB/IPB, ENSAM Talence.

For our experimentations in the classroom we are mainly using the robot Poppy Ergo Jr (real and virutal) and Snap! Our purpose is to improve this pedagogical tools and to create pedagogical activities and resources for teachers.

Figure 4: Experiment robots and pedagogical activities in classroom

- **A pedagogical working group:**
  At the beginning of the project, we established a pedagogical working group of 12 volunteers, teachers from different level (mainly high school teachers of the Aquitaine region) to help to design educational activities in line with the needs of the school curriculum and to test them in the classroom.
  At the beginning of the second year of the project we added 7 other teachers from different background (middle-school and high school teachers) into the group to add more diversity.
  We organised some training to help them to discover and learn how to use the robotics platform, then we met monthly to exchange about the project and to get some feedbacks from them.
  Videos of pedagogical robotics activities are available here:
  https://www.youtube.com/playlist?list=PLdX8RO6QsgB7hM_7SQNLvyp2QjDAkkzLn

- **Experiment and Evaluate the pedagogical kits:**
  Some engineer of the Poppy Education team went to visit the teachers in their school to see and to evaluate the pedagogical tools (robot and activities) in real contexts of use.
  In addition to the observations in classroom, two trainee students of Master 2 in cognitive sciences (M. Demangeat, D. Thibaut) have established an experimental protocol to evaluate the utility and the integration of the pedagogical kits in class. They created and filled out questionnaires by teachers and students. The analyzes of the results are presented in their paper thesis.
  This experimentations are helping us to understand the educational needs, to create and improve the pedagogical tools.

Created pedagogical documents and resources

- **Documentation of Poppy-project**
  We wrote an accessible and clear documentation to help teachers to use and create projects with the robots in the classroom so we rebuilt the existing documentation of the robotics platform Poppy. We added and improve the contents and we used the platform gitbook :
  https://docs.poppy-project.org/en/
- **Pedagogical booklet**
  The pedagogical booklet [178] brings together all the pedagogical activities and project testing in the classroom. It provides guided activities, small challenges and projects to become familiar with the Poppy Ergo Jr robot and the Programming language Snap!
  https://drive.google.com/file/d/0B2jV8VX-lQHwTUxXZjF3OGxHVGM/view

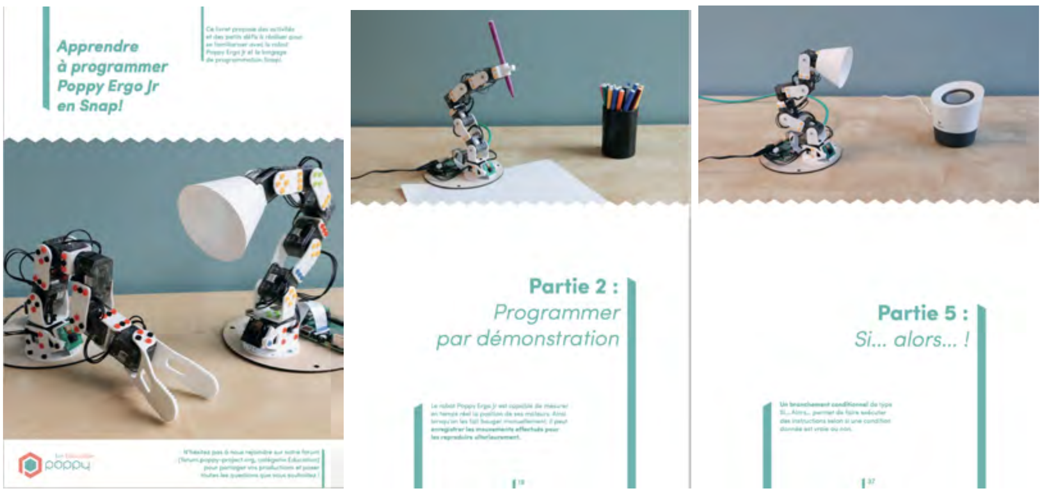


Figure 5: Pedagogical booklet: learn to program the robot Poppy Ergo Jr in Snap!

  The pedagogical activities are also available on the Poppy project forum where everyone is invited to comment and create new ones:
  https://forum.poppy-project.org/t/liste-dactivites-pedagogiques-avec-les-robots-poppy/2305
- **Guide on the pedagogical use of the kit Poppy Ergo Jr in classroom**
  We wrote an article [179] to explain how to use the Robot Ergo Jr in a classroom. It includes a summary of the characteristics of the robots, activities example and give all the necessary resources:
  https://pixees.fr/dans-la-famille-poppy-je-voudrais-le-robot-ergo-jr
- **Demonstration guide to introduce the project**
  This document is for people who already have a little experience with the Poppy Ergo Jr

robot and snap! and wishing to present the project (i.e: to a colleague/acquaintance, on a exhibition stand, during a conference).
The purpose of this document is to provide the necessary elements to enable the Poppy Education project to be presented through the use of Poppy Ergo Jr. robot. The key points of the Poppy Education project and the features of Poppy Ergo Jr kit are presented as well as examples of demonstrations of educational activities (videos and snap! projects) and educational projects (videos). An example of structuring a demo is provided at the end of the document.
https://forum.poppy-project.org/t/guide-de-demo-du-kit-pedagogique-poppy-ergo-jr-version-beta/2698

- **Model of pedagogical activities sheet**
We designed a model of pedagogical activity sheet. It helps us to get back the various activities and allows to have a homogeneous presentation. It is simpler to share and get back the creations of each.
https://forum.poppy-project.org/t/modele-de-fiche-pedagogique-telechargeable-pour-les-activites-robotiques/2706

3.4.3 Popular science books, talks and interviews

Beyond these projects, we have been strongly involved in popular science activities, involving regular writing of popular science articles, participation to wide audience radio and tv programs and intervention in the press to address scientific issues (e.g. Le Monde, Les Echos, France Inter, France Info, France Culture, ...), participation to science festivals and museum exhibitions.

Highlights include:

- Didier Roy was award the prize Serge Hocquenguem for his work on educational robotics, http://psh.aid-creem.org/spip.php?rubrique1 et http://binaire.blog.lemonde.fr/2016/12/09/pourquoi-didier-et-eva-jouent-avec-le-meme-robot/
- Pierre-Yves Oudeyer gave in 2014 a TedX talk (https://www.youtube.com/watch?v=AP8i435ztwE, video viewed by more than 14000 people).
- Popular science book: Audouze, J., Chapouthier, G., Laming, D., Oudeyer, P-Y. (2015) Mondes Mosaiques: Astres, villes, vivant et robots, CNRS Editions.
- Popular science book: Oudeyer, P-Y. (sept. 2013) Aux sources de la parole: auto-organisation et évolution, Odile Jacob, Paris.

Links to furthers popular science talks by the team:

- Selected list of popular science articles, videos and events: http://www.pyoudeyer.com/popular-science/
- Selected list of interventions in the press: http://www.pyoudeyer.com/press/
- Popular science talks and demos in 2016: https://irabot.inria.fr/RA2016/flowers/uid452.html
- Popular science talks and demos in 2015: https://raweb.inria.fr/rapportsactivite/RA2015/flowers/uid407.html
- Popular science talks and demos in 2014: https://raweb.inria.fr/rapportsactivite/RA2014/flowers/uid276.html
- Popular science talks and demos in 2013:https://raweb.inria.fr/rapportsactivite/RA2013/flowers/uid299.html

4 Objectives for the next four years

Developmental processes allow humans, and especially infants, to continuously acquire novel skills and adapt to their environment over their entire lifetime. They do so autonomously, through self-exploration and social interaction with their peers, and without the need for an "engineer" to open and retune the brain and the environment specifically for each new task. Machines and robots have been so far very far from such developmental capabilities, even for life-long learning of relatively simple sensorimotor skills.

Human and biological sciences have identified various families of developmental mechanisms that are key to explain how infants can acquire so robustly a wide diversity of skills [Joh05, Mil11], in spite of the complexity and high-dimensionality of the body [Ber67b] and the open-endedness of its potential interaction with the physical and social environment.

This research program focuses on a selected set of these developmental mechanisms and their interaction (active exploration, intrinsic motivation, maturation, imitation, joint attention, properties of embodiment), with three complementary goals:

- Robotics and AI: Studying how these developmental mechanisms can be functionally formalized and transposed in robots and explore how they can allow robots to be equipped with important aspects of developmental capabilities observed in humans.
- Cognitive Sciences: Elaborating computer and robotic models as tools for understanding particular aspects of human development.
- Applications: Using these techniques and new understanding of human learning and development for applications in the educational technologies.

4.1 Active exploration algorithms for life-long learning of sensorimotor skills in robots

The Technical Challenges. This part of the program focuses on two technical challenges that need to be addressed for the autonomous acquisition of repertoires of sensorimotor skills (here related to the learning of how to control an unknown body and/or its physical interaction with unknown external objects) in robots: 1) How can a robot acquire autonomously, efficiently and robustly new skills, involving the learning of forward and inverse models in large high-dimensional inhomogeneous sensorimotor spaces? Forward models, denoted $(S(t),A(t)) \rightarrow S(t+1)$, where $S(t)$ is the state of the embodied machines at time t and $A(t)$ encodes the parameters of action primitives or policy, allow the robot to predict the consequences of its actions in given contexts (e.g. how an object moves when pushed in a given manner). Inverse models $\tau_\theta \rightarrow \pi_\theta$ allow a robot to determine which policy of action π_θ to use in order to achieve the objective τ_θ in its task space (e.g. which push movement to make in order to have an object move in a given way); 2) How can a robot learn autonomously and continuously novel reusable skills without needing that an engineer reprograms a new specific cost function to be optimized for each new task [OKH07a]?

These two technical challenges are very difficult for several reasons. One important reason is the combination of three facts: 1) They involve the regression learning of mappings (forward and inverse models) between spaces (encoding states and actions) which are typically continuous, high-dimensional, and inhomogeneous; 2) Learning examples have to be collected autonomously and incrementally by a physical robot (no clean database can be provided by an engineer); 3) Learning happens through self-experimentation and observation in the physical world, which takes time and thus strongly limits the number of examples that can be collected.

Advanced statistical learning techniques dedicated to high-dimensional regression have been elaborated recently, such as LWPR, Gaussian Processes or Support Vector Regression [NTP11, SSP11], and we use them as building blocks. Yet, because they were designed assuming that an adequate database of learning examples was provided, the three facts mentioned above make that fundamental complementary mechanisms for guiding and constraining autonomous exploration and learning are needed. This research program explores the formalization and use of developmental mechanisms for active exploration to address this challenge.

Intrinsic motivation for active learning of forward and inverse models. Inspired by brain mechanisms which drive infants to explore new skills for the mere pleasure of novelty/learning/surprise/challenge, called intrinsic motivation and identified both in psychology [38] and neuroscience [25], algorithms were developed for efficient organized curiosity-driven exploration of large high-dimensional sensorimotor spaces in robots (i.e. curiosity-driven autonomous collection of learning examples) [27, 16, 37]. Those algorithms share similarities with other algorithms in optimal experiment design in statistics [Fed72] and active learning [CGJ96], but have specific properties which make them uniquely applicable to the real-world sensorimotor spaces of robots [163]. In particular, instead of pushing the system to search for sensorimotor observations of maximal novelty/uncertainty/entropy, they use the derivative of the prediction ability/uncertainty/entropy of the models being learnt by the system [OKH07a] which allows to actively control the growth of complexity in exploration of large spaces. We will investigate how they need to be updated to scale to much larger and longer experiments allowing robots to learn autonomously multiple motor primitives, controlling many objects and over a time span of several weeks. To achieve this, we will continue the work begun to study the landscape of possible formalization and computational measures of "learning progress" as presented in [16, 37, 27], in particular by designing active learning algorithms working in tasks spaces, such as SAGG-RIAC ([27]) which will be extended to multiple control and task spaces through a hierarchical version of the mechanism of active model exploration [87, 88], and use multi-scale probabilistic representation, based on decision trees, of the quality of predictive models, and very importantly by using the strategic learning algorithmic framework [LO12b, NO12a] to leverage the synergies between intrinsic motivation and maturation [BO11], imitation [37] and embodiment [KO07].

Data efficient learning using deep reinforcement learning algorithms in curiosity-driven exploration algorithms. Algorithms based on active learning of inverse models (e.g. active goal babbling [27]) have shown how direct policy search methods [53] could be integrated in architectures allowing to acquire efficiently fields of continuous parameterized skills in real world problems. However, the use of direct policy search appears to be suboptimal in terms of sample complexity. Another line of research has shown how deep reinforcement learning algorithms could be adapted for the problem of learning continuous control policies with low sample complexity, such as with the DDPG algorithm [LHP$^+$15]. However, these deep RL techniques have so far only considered learning single skills. This project will study how deep RL algorithms can be made to work with parameterized reward functions, and through this parameterization be integrated in an algorithmic architecture for curiosity-driven goal babbling allowing to learn repertoires of parameterized skills (together with their representations). Experiments will extend the Explauto open-source library [129] for the algorithms, and use the openAI Gym toolkit [DCH$^+$16] for benchmarking these algorithms.

Curiosity-driven learning of hierarchies and representations of skills, tasks and environments. A crucial feature of open-ended cognitive development is the capability to build progressively new abstractions, i.e. to acquire higher-level skills that combine several lower-level skills as well as new representation that allow better generalization and understanding of the world. A major challenge is that considering combinations of lower-level skills and spaces of new representations leads to an explosion of search spaces, which is a problem for embodied organisms due to limited time, energy and cognitive resources. Here we will study how curiosity-driven learning mechanisms can contribute to organizing such acquisition of hierarchies of skills and representations in robots. In particular, we will:

- 1) Study and experiment on robots how techniques for hierarchical reinforcement learning [Bot12], in particular option theory [SPS99], who have used so far discrete spaces of actions,

can be combined with techniques for active learning of high-dimensional inverse sensorimotor models [27] in order to allow a robot to build actively hierarchies of skills combining policies based on high-dimensional actions; In particular, we will investigate how to integrate intrinsic motivation in model-based hierarchical reinforcement learning (and within a Deep RL framework), as a mechanism for generating and selecting "interesting" options in SMDPs [SPS99].
- 2) Study how techniques of multimodal deep learning [HS06, NKK^{+}11] can be used to select useful manifold in high-dimensional sensorimotor flows (i.e. find useful lower dimensional abstractions of the flows) on which skill acquisition techniques of point 1) can be applied.

Tools and methodology for long-term robot learning experiments. An important limit of our previous research (also applying to other teams in the domain) is that algorithms and architectures developed so far have been tested only in real robot experiments during less than one day, mainly because no existing robot experimental platform is robust or safe enough for longer experiments. This is problematic since the purpose is to allow life-long learning. To address this issue, we will continue to develop the open-source Poppy robotic platform, which combines technological elements in such a way that experiments during several months become possible, being at the same time affordable, robust and safe. We will use this platform for large-scale evaluation of the above mentioned algorithms. As it is open-source hardware and software, the general Developmental Robotics and Robot Learning communities can benefit from it.

4.2 Computational modelling for understanding human active exploration and information seeking

Intrinsic motivation for curiosity-driven visual attention and exploration in humans and monkeys. Models of intrinsic motivation based on learning progress are not only useful for efficient robot development: they provide original hypothesis [38, 25], and testable predictions, related to spontaneous exploration in humans. In particular, it has been proposed that the brain is intrinsically motivated to explore activities of intermediate complexity, neither too easy nor too difficult, and which provide maximum learning progress [38]. Other formulations are based on measures of uncertainty reduction in a Bayesian framework [MB13, FAPB12]. Through a collaboration with cognitive neuroscientist Jacqueline Gottlieb (Columbia Univ., NY, US) and with developmental psychologist Celeste Kidd (Univ. Rochester, US), we will set-up behavioural and neuro-imaging experiments that allow to test these hypothesis when applied to visual, manual and epistemic exploration in humans and monkeys. Within the theoretical framework of these models, we will study the factors that influence such curiosity-driven exploration and their variability across individuals and species:

- 1) These experiments will consist in setting up discovery activities, where human children, human adults and monkeys will be free to explore and learn about alternative programmable interactive (for e.g. using educational programmable mobile robots like the Thymio 2). In each experiment, several factors such as complexity, novelty and number of objects will be varied. Such experiments will be conducted with humans of various ages, as well as with monkeys. What will be studied is: selection of theoretical hypothesis that match the observed organization of exploration; factors that influence the structuration of exploration; variability across individuals, ages and species.
- 2) New computational models will be developed to account for the variability and factors identified in the experiments. They will be based on a combination of the Bayesian formalism, action selection mechanisms based on multi-armed bandit techniques, and information theory, and robotic experiments will be conducted where the robot is placed in the same discovery situations as infants in 1).

This collaboration, already began in the context of a Fullbright grant, and now supported by HFSP project “Curiosity” and Inria associated team “Neurocuriosity”, is planned to extend over at least 5 years given the very long time scale needed to set-up and analyze experiments with humans and monkeys.

4.3 Applications to educational technologies

Active teaching algorithms for intelligent tutoring systems. In collaboration with educational experts from Rectorat d’Aquitaine, we will continue to develop applications of algorithms and models of curiosity-driven learning in the domain of intelligent tutoring systems. This project aims at developing methodologies and software which adaptively personalize sequences of learning activities to the particularities of each individual student. We will improve and evaluate new versions of our ZPDES and Riarit systems that aim at proposing to each particular student the right activity at the right time, maximizing concurrently his learning progress and its motivation through incremental interaction (as opposed to other machine learning approaches building teaching strategies based for an “average” student). In addition to contributing to the efficiency of learning and motivation, the approach is also made to reduce the time needed to design ITS systems. Beyond our first results showing that using multi-armed bandit algorithms that maximize empirical measures of learning progress, and tested in real world conditions in primary schools, we will work on several lines of improvement: 1) we will develop algorithms that can both leverage data from single learners and data from pools of learners to accelerate the calibration phase for each person. This includes learning parameterized learner models; 2) we will develop hybrid control algorithm which instead of imposing an exercise at each step to students, recommend several alternatives to choose from in order to let learners express their preferences and leverage this information in the algorithm; 3) we will develop methods to assess the motivational impact and usability of these systems in addition to learning efficiency, in real classroom conditions.

Educational robotics. Within the Feder project Poppy Education, as well as within the eFran project “Perseverons”, both in collaboration with national educational institutions, we will continue to develop adaptations of the open-source Poppy robotic platform as well as pedagogical content that stimulate curiosity-driven enquiry and learning. We will extend the current Poppy Ergo platform, that is currently used in colleges and lycées for experimentation, by designing a visual programming environment that implements programming activities which sequences can be personalized with the active teaching algorithms described above through hybrid feedback from the visual interface and from physical interaction between the robot and its environment. The system will be evaluated along several dimensions: 1) usability in real classroom for both students and teachers; 2) impact on learning in the context of acquisition of computer science basic concepts.

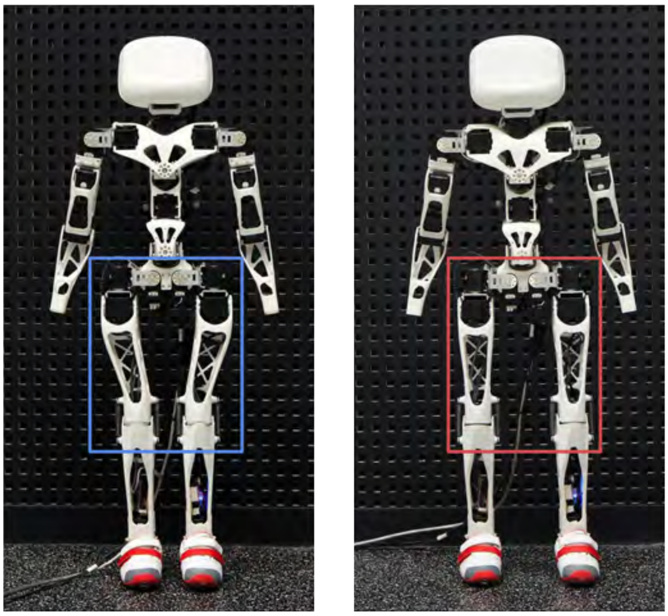
4.4 Hardware

4.4.1 Open-source 3D printed Poppy robotic platform

The Poppy Platform is open-source 3D printed robotic platform, consisting of several robots using the same basic technological bricks, developed by the Flowers team. It is based on robust, flexible, easy-to-use and reproduce hardware and software. In particular, the use of 3D printing and rapid prototyping technologies is a central aspect of this project, and makes it easy and fast not only to reproduce the platform, but also to explore morphological variants. Poppy targets three domains of use: science, education and art (see `http://www.poppy-project.org`).

Poppy was initially designed with a scientific objective, aiming to be a new experimental platform opening the possibility to systematically study the role of morphology in sensorimotor control, in human-robot interaction and in cognitive development. Indeed, a suitable design of a robot morphology can greatly simplify control problems, increase robustness, and open new modes of interaction with the physical and social world. Thus, being able to study the body as an experimental variable, something which can be systematically changed and experimented, is of paramount importance. Yet, until recently it was complicated because building a robot relied on heavy and costly manufacturing techniques. 3D printing has changed the landscape of what is possible: Poppy Project transposed it to robotics (humanoids and smaller-scale robots), and it is now possible to explore new body shapes in just a few days. It enables and simplifies the experimentation, the reproduction and the modification of the morphology in research laboratories. It also allows collaborative working, sharing and replication of the results on these issues between laboratories. The ambition is to become a reference platform for benchmarking and dissemination of scientific results.

Thanks to the fact that it integrates advanced and yet easily accessible techniques in an embodiment that motivates students and the wider public, this platform also meets a growing societal need: education and training in technologies combining computer science, electronics and mechanics, as well as a training tool to the emergent revolutionary 3D printing process. With its openness, its design and its rather low-cost, Poppy provides a unique context for experimentation and learning of these technologies in a Do-It-Yourself (DIY) approach. Finally, the possibility to easily modify both the hardware and the software also makes Poppy a useful tool for artistic projects working with interactive computerized installations.



(a) bended thighs (b) straight thighs

Figure 6: The Poppy Humanoid robot

Open-Source Robotic Platform Poppy Humanoid (see figures) was the first complete 3D printed open-source and open-hardware humanoid robot. Its 3D printed skeleton and its Raspberry Pi-based electronics are open-hardware (Creative Commons). Its software is open-source (GPL V3), and allows programming beginners as well as advanced roboticists to control the robot in Python thanks to the PyPot library (https://github.com/poppy-project/pypot). Its motors are common off-the-shell Robotis actuators (http://www.robotis.com/xe/dynamixel_en), and allow for compliant control and soft physical human-robot interaction. Poppy presents

Figure 7: Poppy Torso and Poppy Ergo robots: the Poppy platform allows easy conception, building and programming of various robotic shapes

Figure 8: The Poppy platform is used in various educational contexts, ranging from computer science courses to artistic courses

Figure 9: Poppy Ergo Jr, 6-DoFs arm robot for education

an original mechanical structure which permits to obtain a light structure with 3.5kg for 84cm height. Before the arrival of 3D printing techniques, this kind of complex structure was either impossible to produce or extremely expensive. Now, anyone can produce and modify such robot in their home using affordable personal 3D printers.

Poppy Humanoid and Poppy Torso web sites: https://www.poppy-project.org/en/robots/poppy-humanoid

Poppy Ergo Jr is an open hardware robot developed by the Poppy Project to explore the use of robots in classrooms for learning robotic and computer science. It is available as a 6 or 4 degrees of freedom arm designed to be both expressive and low-cost. This is achieved by the use of FDM 3D printing and low cost Robotis XL-320 actuators. A Raspberry Pi camera is attached to the robot so it can detect object, faces or QR codes. The Ergo Jr is controlled by the Pypot library and runs on a Raspberry pi 2 or 3 board. Communication between the Raspberry Pi and the actuators is made possible by the Pixl board we have designed. The Poppy Ergo Jr robot has several 3D printed tools extending its capabilities. There are currently the lampshade, the gripper and a pen holder.

Poppy Ergo Jr web site : https://www.poppy-project.org/en/robots/poppy-ergo-jr

These robotic platforms come with associated simulators, as well as several easy-to-use programming interfaces ranging from python to the visual programming languages like Snap !.

Collaboration tools Several web tools support collaboration and sharing among members of the Poppy community:

- a portal web site (www.poppy-project.org),
- GitHub repositories for the hardware and software with associated wikis for documentation (www.github.com/poppy-project/)
- and a forum based on Discourse (www.discourse.org) technology (forum.poppy-project.org).

Maturity, impact and dissemination Poppy Humanoid, Poppy Torso and Poppy Ergo are now commercial products distributed by Generation Robots company, based on a contract betwenn Inria and Gneration Robots for the exploitation of the Poppy trademark deposited in 10 countries (https://www.generationrobots.com/fr/279-poppy). There are more than 1200 users and/or contributors on the Poppy forum, and several hundred Poppy Ergo robots were sold by Generation Robots. The robotic platform is used in standard curriculum by students and teachers in 15 colleges and high schools, in several engineering schools (e.g. Ensam Bordeaux and Paris, Enseirb, ENST Brest), integrated as the educational platform in national large scaled educational projects (e.g. Class Code, Perseverons). It is used in FabLabs and science museums in Paris, Bordeaux, Rennes, Grenoble, Caen, Toulouse, and several towns in Spain, UK, Germany and the US. It has also been used in several international artistic projects and associated public performances (e.g. http://shonen.info/schoolofmoon/ or http://www.poppynz.com). The platform was selected as finalist for the Global Fab Award 2014, (https://www.fab10.org/en/awards) which select the best worldwide projects in the Makers ecosystem.

Poppy robots were presented in highly visible and prestigious wide audience venues (François Hollande at Elysée, Axelle Lemaire in Bordeaux, Sénat, Le Web conference, Tedx Cannes), in numerous high quality media/press articles (full pages in Le Monde, Les Echos, Libération, interviews on France Inter, France Info as well as in international press such as Scientific American, El Mundo, japanese TV, https://www.poppy-project.org/in-the-press/), allowing **millions of persons to discover aspects of the activities of Inria**. It was featured in the report of the ministry of research for defining the National Research Strategy towards 2020 ("Stratégie Nationale de Recherche France 2020". Leveraging this visibility, the trademark "Poppy"). The

Poppy trademark was protected in 10 countries and its exploitation forms a pillar of the economic exploitation of Poppy.

About the educational perspectives of the Poppy project, the European Commissioner for Research and Innovation, Máire Geoghegan-Quinn, declared : ”This is a great offshoot of an ERC project: a low-cost platform that could foster a more interactive and inspiring learning environment, allowing students to connect with research and design.” (http://erc.europa.eu/sites/default/files/press_release/files/ERC_highlight_Poppy.pdf).

Startup Company A spin off of this project has been the creation of the startup company Pollen Robotics (created in may 2016) as a spinoff of the Flowers team, and targets to exploit some the underlying technologies of the Poppy platform towards low-cost robotics for everyone.

Web site: http://pollen-robotics.com/en/

Scientific Impact Beyond the applications in the educational domain, the Poppy robotic platforms also have a strong scientific impact. Poppy Humanoid and Poppy Torso are the world first humanoid robots to be both open-source and 3D printed which facilitate the exploration of morphological variability. This is a major scientific issue for Human-Robot interaction and control theory. For example, the Hybrid laboratory from “institut de Neurosciences Intégratives” in Bordeaux uses the Poppy platform to develop and study new myoelectric robotic prosthesis with the aim of improving life conditions for disabled persons (http://www.incia.u-bordeaux1.fr/spip.php?article340). Moreover, the Poppy platform opens up new perspectives in artificial intelligence and automatic learning as it allows non-robotic researchers to easily experiment complex learning algorithms. This is made possible through the control softwares and the fact that dangerous motions for the robot can be tested as its parts are easily replaceable. In particular, the Flowers team is now using the platform to test and demonstrate its artificial curiosity algorithms, as shown in the demonstration organized during the NIPS 2016 conference. It has been awarded 2nd best demonstration while competing with demonstrations from companies like Google, Deepmind, Microsoft, Facebook, and some major English university laboratories https://www.youtube.com/watch?v=NOLAwD4ZTW0.

4.5 Software

4.5.1 Explauto: A library to study, model and simulate intrinsically motivated multitask learning and exploration in virtual and robotic agents

Scientific Description Explauto is a framework developed to study, model and simulate curiosity-driven learning and exploration in real and simulated robotic agents. Explauto's scientific roots trace back from Intelligent Adaptive Curiosity algorithmic architecture [OKH07b], which has been extended to a more general family of autonomous exploration architectures by [16] and recently expressed as a compact and unified formalism [126]. The library is detailed in [129]. In Explauto, interest models are implementing the strategies of active selection of particular problems / goals in a parametrized multi-task reinforcement learning setup to efficiently learn parametrized policies. The agent can have different available strategies, parametrized problems, models, sources of information, or learning mechanisms (for instance imitate by mimicking vs by emulation, or asking help to one teacher or to another), and chooses between them in order to optimize learning (a process called strategic learning [37]). Given a set of parametrized problems, a particular exploration strategy is to randomly draw goals/ RL problems to solve in the motor or problem space. More efficient strategies are based on the active choice of learning experiments that maximize learning progress using bandit algorithms, e.g. maximizing improvement of predictions or of competences to solve RL problems [OKH07b]. This automatically drives the system to explore and learn first easy skills, and then explore skills of progressively increasing complexity. Both random and learning progress strategies can act either on the motor or on the problem space, resulting in motor babbling or goal babbling strategies.

- Motor babbling consists in sampling commands in the motor space according to a given strategy (random or learning progress), predicting the expected effect, executing the command through the environment and observing the actual effect. Both the parametrized policies and interest models are finally updated according to this experience.
- Goal babbling consists in sampling goals in the problem space and to use the current policies to infer a motor action supposed to solve the problem (inverse prediction). The robot/agent then executes the command through the environment and observes the actual effect. Both the parametrized policies and interest models are finally updated according to this experience.It has been shown that this second strategy allows a progressive solving of problems much more uniformly in the problem space than with a motor babbling strategy, where the agent samples directly in the motor space [16].

Functional Description This library provides high-level API for an easy definition of:

- Real and simulated robotic setups (Environment level),
- Incremental learning of parametrized policies (Sensorimotor level),
- Active selection of parametrized RL problems (Interest level).

The library comes with several built-in environments. Two of them corresponds to simulated environments: a multi-DoF arm acting on a 2D plan, and an under-actuated torque-controlled pendulum. The third one allows to control real robots based on Dynamixel actuators using the Pypot library. Learning parametrized policies involves machine learning algorithms, which are typically regression algorithms to learn forward models, from motor controllers to sensory effects, and optimization algorithms to learn inverse models, from sensory effects, or problems, to the motor programs allowing to reach them. We call these sensorimotor learning algorithms sensorimotor models. The library comes with several built-in sensorimotor models: simple nearest-neighbor look-up, non-parametric models combining classical regressions and optimization algorithms, online mixtures of Gaussians, and discrete Lidstone distributions. Explauto sensorimotor models are online learning algorithms, i.e. they are trained iteratively during the interaction of the robot in the environment in which it evolves. Explauto provides also a unified interface to define exploration strategies using the InterestModel class. The library comes with two built-in interest models: random sampling as well as sampling maximizing the learning progress in forward or inverse predictions.

Explauto environments now handle actions depending on a current context, as for instance in an environment where a robotic arm is trying to catch a ball: the arm trajectories will depend on the current position of the ball (context). Also, if the dynamic of the environment is changing over time, a new sensorimotor model (Non-Stationary Nearest Neighbor) is able to cope with those changes by taking more into account recent experiences. Those new features are explained in Jupyter notebooks.

This library has been used in many experiments including:

- the control of a 2D simulated arm,
- the exploration of the inverse kinematics of a poppy humanoid (both on the real robot and on the simulated version),
- acoustic model of a vocal tract.

Explauto is crossed-platform and has been tested on Linux, Windows and Mac OS. It has been released under the GPLv3 license.

- Contact: Sébastien Forestier
- URL: https://github.com/flowersteam/explauto

4.5.2 Pypot

Scientific Description Pypot is a framework developed to make it easy and fast to control custom robots based on Dynamixel motors. This framework provides different levels of abstraction corresponding to different types of use. Pypot can be used to:

- control Robotis motors through a USB2serial device,
- define the structure of a custom robot and control it through high-level commands,
- define primitives and easily combine them to create complex behavior.

Pypot is part of the Poppy project. It is the core library used by the Poppy robots. This abstraction layer allows to seamlessly switch from a given Poppy robot to another. It also provides a common set of tools, such as forward and inverse kinematics, simple computer vision, recording and replaying moves, or easy access to the autonomous exploration library Explauto.

To extend pypot application domains and connection to outside world, it also provides an HTTP API. On top of providing an easy way to connect to smart sensors or connected devices, it is notably used to connect to Snap!, a variant of the well-known Scratch visual programming language.

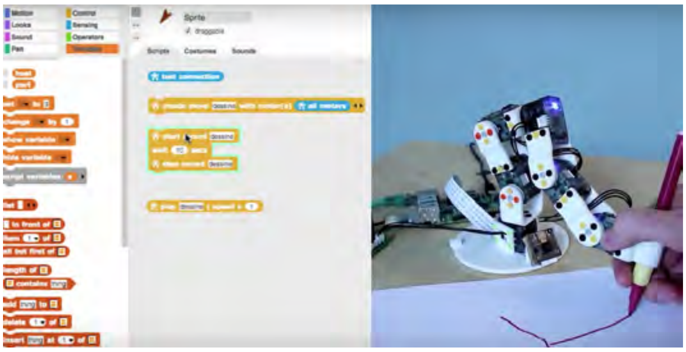


Figure 10: Example of using pypot (with Snap! visual programming frontend) to program a robot to reproduce a drawn shape

Functional Description Pypot is entirely written in Python to allow for fast development, easy deployment and quick scripting by non-expert developers. It can also benefit from the scientific and machine learning libraries existing in Python. The serial communication is handled through the standard library and offers high performance (10ms sensorimotor loop) for common Poppy uses. It is cross-platform and has been tested on Linux, Windows and Mac OS.

Pypot is also compatible with the V-REP simulator. This allows the transparent switch from a real robot to its simulated equivalent with a single code base.

Finally, it has been developed to be easily and quickly extended for other types of motors and sensors.

It works with Python 2.7 or Python 3.3 or later, and has also been adapted to the Raspberry Pi board.

Pypot has been connected to Snap!, a variant of the famous Scratch visual language, developed to teach computer science to children. It is based on a drag-and-drop blocks interface to write scripts by assembling those blocks.

Thanks to the Snap! HTTP block, a connection can be made to pypot allowing users to directly control robots through their visual interfaces. A set of dedicated Snap! blocks have been designed, such as *set motor position* or *get motor temperature*. Thanks to the Snap! HTTP block, users can control robots through this visual interfaces connecting to pypot. A set of dedicated Snap! blocks has been designed, such as *set motor position* or *get motor temperature*.

Figure 11: Using Snap! to program a robot by demonstration and create complex choreographies

Snap! is also used as a tool to program the robot by demonstration. Using the *record* and *play* blocks, users can easily trigger kinesthetic recording of the whole robot or only a specific subpart, such as an arm. These records can then be played or "mixed" - either played in sequence or simultaneously - with other recordings to compose complex choreographies. The moves are encoded as a model of mixture of Gaussian (GMM) which allows the definition of clean mathematical operators for combining them.

This recording tool has been developed and used in collaboration with artists who show interest in the concept of robotic moves.

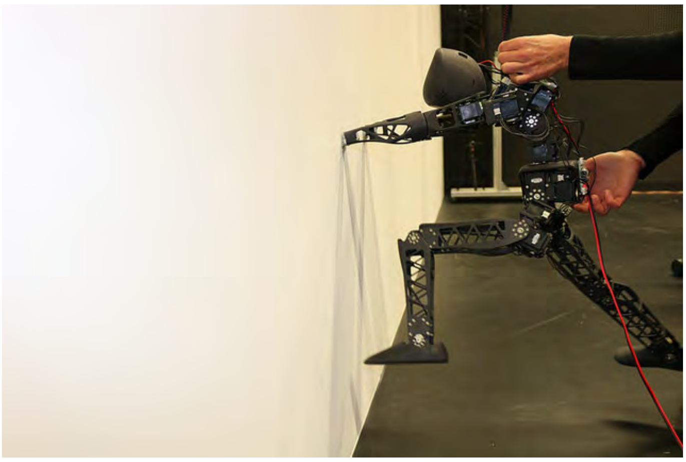


Figure 12: Artistic project exploring the concept of robotic move.

- Participants: Pierre Rouanet, Matthieu Lapeyre, Steve Nguyen, Damien Caselli and Theo Segonds
- Contact: Theo Segonds
- URL: https://github.com/poppy-project/pypot

4.5.3 KidLearn: a library for personalization algorithms in intelligent tutoring systems

Keyword: Automatic Learning

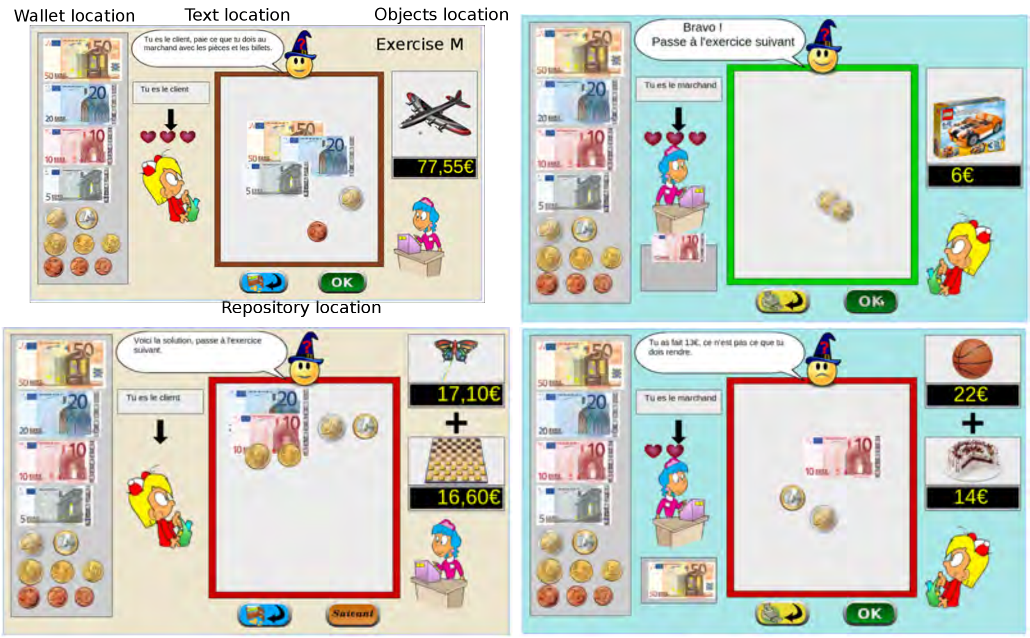


Figure 13: Four principal regions are defined in the graphical interface. The first is the wallet location where users can pick and drag the money items and drop them on the repository location to compose the correct price. The object and the price are present in the object location. Four different types of exercises exist: M : customer/one object, R : merchant/one object, MM : customer/two objects, RM : merchant/two objects.

Functional Description KidLearn is a software which adaptively personalize sequences of learning activities to the particularities of each individual student. It aims at proposing to the student the right activity at the right time, maximizing concurrently his learning progress and its motivation. The library regrouping the different developed technologies is available on github.

The games is instantiated in a browser environment where students are proposed exercises in the form of money/token games (see Figure 13). For an exercise type, one object is presented with a given tagged price and the learner has to choose which combination of bank notes, coins or abstract tokens need to be taken from the wallet to buy the object, with various constraints depending on exercises parameters. The games have been developed using web technologies, HTML5, javascript and Django.

- Participants: Benjamin Clement, Pierre Yves Oudeyer, Didier Roy and Manuel Lopes
- Contact: Manuel Lopes
- URL: `https://flowers.inria.fr/research/kidlearn/`
- URL: `https://github.com/flowersteam/kidlearn`

4.5.4 KidBreath: a software for experimenting personalization algorithms in e-health systems

Functional Description KidBreath is a web responsive application composed by several interactive contents linked to asthma and displayed to different forms: learning activities with quiz, short games and videos. There are profil creation and personalization, and a part which describes historic and scoring of learning activities, to see evolution of Kidreath use. To test Kidlearn algorithm, it is iadapted and integrated on this platform. Development in PHP, HTML-5, CSS, MySQL, JQuery, Javascript. Hosting in APACHE, LINUX, PHP 5.5, MySQL, OVH.

- Partner: ItWell SAS
- Contact: Alexandra Delmas
- URL: http://www.kidbreath.fr

4.5.5 DMP-BBO: Black-Box Optimization for Dynamic Movement Primitives

Functional Description The DMP-BBO Matlab library is a direct consequence of the insight that black-box optimization outperforms reinforcement learning when using policies represented as Dynamic Movement Primitives. It implements several variants of the PIBB algorithm for direct policy search. The dmp-bbo C++ library has been extended to include the "unified model for regression". The implementation of several of the function approximators have been made real-time compatible.

- Participant: Freek Stulp
- Partner: ENSTA
- Contact: Freek Stulp
- URL: https://github.com/stulp/dmpbbo

4.5.6 PEDDETECT: real-time person detection

Functional Description PEDDETECT implements real-time person detection in indoor or outdoor environments. It can grab image data directly from one or several USB cameras, as well as from pre-recorded video streams. It detects mulitple persons in 800x600 color images at frame rates of ¿15Hz, depending on available GPU power. In addition, it also classifies the pose of detected persons in one of the four categories "seen from the front", "seen from the back", "facing left" and "facing right". The software makes use of advanced feature computation and nonlinear SVM techniques which are accelerated using the CUDA interface to GPU programming to achieve high frame rates. It was developed in the context of an ongoing collaboration with Honda Research Institute USA, Inc.

- Participant: Alexander Gepperth
- Contact: Alexander Gepperth

4.5.7 3rd Hand Infrastructure

Scientific Description Robots have been essential for keeping industrial manufacturing in Europe. Most factories have large numbers of robots in a fixed setup and few programs that produce the exact same product hundreds of thousands times. The only common interaction between the robot and the human worker has become the so-called 'emergency stop button'. As a result, reprogramming robots for new or personalized products has become a key bottleneck for keeping manufacturing jobs in Europe. The core requirement to date has been the production in large numbers or at a high price. Robot-based small series production requires a major breakthrough in robotics: the development of a new class of semi-autonomous robots that can decrease this cost substantially. Such robots need to be aware of the human worker, alleviating him from the monotonous repetitive tasks while keeping him in the loop where his intelligence makes a substantial difference.

In this project, we pursue this breakthrough by developing a semi-autonomous robot assistant that acts as a third hand of a human worker. It will be straightforward to instruct even by an untrained layman worker, allow for efficient knowledge transfer between tasks and enable a effective collaboration between a human worker with a robot third hand.

The main contributions of this project are the scientific principles of semi-autonomous human-robot collaboration, a new semi-autonomous robotic system that is able to: i) learn cooperative tasks from demonstration; ii) learn from instruction; and iii) transfer knowledge between tasks and environments.

The results led to a specific robotic software infrastructure for semi-autonomous robots that targets theses principles in terms of vision, path planning, decision-making, machine learning and motor control. Some of these topics have been addressed by our partners, we are discussing here our contributions to the infrastructure.

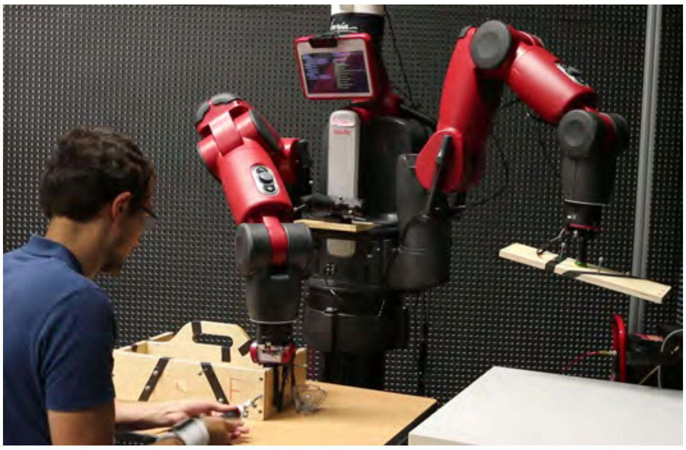


Figure 14: Collaborative toolbox assembly with a semi-autonomous robot

Functional Description The core of this software infrastructure relies on predicates. The robot represents the scene as a set of predicates reflecting the position and state of objects, as well as the activities of human operators. Although we implemented different modalities to instruct the robot including teleoperation and scripted actions, our main contribution is the learning-by-demonstration modality. This feature is provided by planning in relational domains [130] and the RAP framework [145] (Relational Activity Processes) allowing to plan concurrent robot actions learned from relational policies.

The robot can be instructed from different interaction modalities including voice, gesture and graphical user interface [125]. The latest allows the user to visualize the robot uncertainty about the task and correct the robot in case of mistake. They are also a way to perform active learning so that the robot can ask questions to the operator if it does not manage to plan actions.

The infrastructure also provides ways to instruct motions to the robot via kinesthetic teaching and learning natural motions by observing demonstrated human movements . Motions are stored via probabilitic motor primitives. These primitives are learned in joint-space but also keep track of the task-space motions so that new goals can be planned from task-space constraints. The robot can take into account the operator's body to handover objects in a way that prevents musculosketetal diseases and maximises his comfort.

- Contact: Yoan Mollard
- https://github.com/3rdHand-project/thr_infrastructure

4.5.8 Of 3-D point cloud

Functional Description This software scans the 3-D point cloud of a scene to find objects and match them against a database of known objects. The process consists in 3 stages. The segmentation step finds the objects in the point cloud, the feature extraction computes discriminating properties to be used in the classification stage for object recognition.

- Participants: David Filliat, Alexander Gepperth and Louis-Charles Caron
- Contact: Alexander Gepperth

4.5.9 Self-calibration BCI - Matlab library

Functional Description The Matlab software implements the algorithms described in [97]. Downloadable from https://github.com/jgrizou/lfui.

It allows a robot to be instructed a new task by a human using communicative signals initially totally unknown to the robot. It is was extended and improved in the context of EEG-based brain-machine interfaces (BMIs) [96].

It results in a BCI based control of sequential tasks with feedback signals that do not require any calibration process. As a by-product, the method provides an unsupervised way to train a decoder with the same performance than state-of-the-art supervised classifiers, while keeping the system operational and solving, with a lower performance during the first steps, the unknown task. The algorithm has been tested with online experiments (fig. 4.5.9), showing that the users were able to guide from scratch an agent to a desired position.

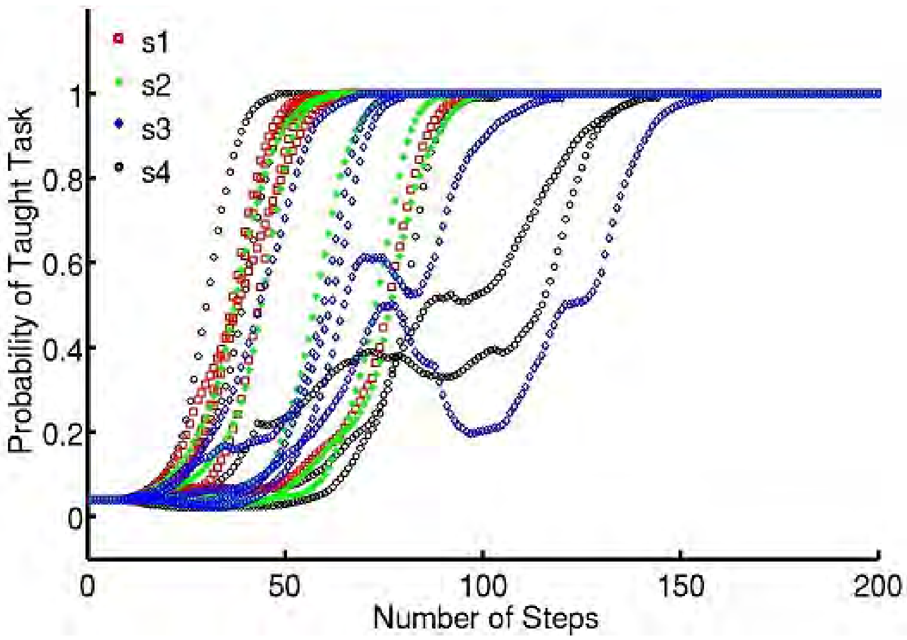


Figure 15: Results from the online BCI experiment for identifying the task. Evolution of the probability of the taught task for each subject and run

To improve the efficiency of the algorithm, we introduced a new planning method that uses the uncertainty in the signal-target estimation. This planner is inspired by exploration methods with exploration bonuses that allow guiding to reduce the uncertainty in an efficient way. We showed that trying to follow the best hypothesis does not explore the space significantly to reduce uncertainty and thus identify the correct task. Only through an approach that plans how to reduce the uncertainty multiple steps ahead are we sure that the agent will reach states that can only be explained by the correct hypothesis.

- Participants: Jonathan Grizou, Iñaki Iturrate, Luis Montesano, Manuel Lopes and Pierre-Yves Oudeyer
- Contact: Jonathan Grizou

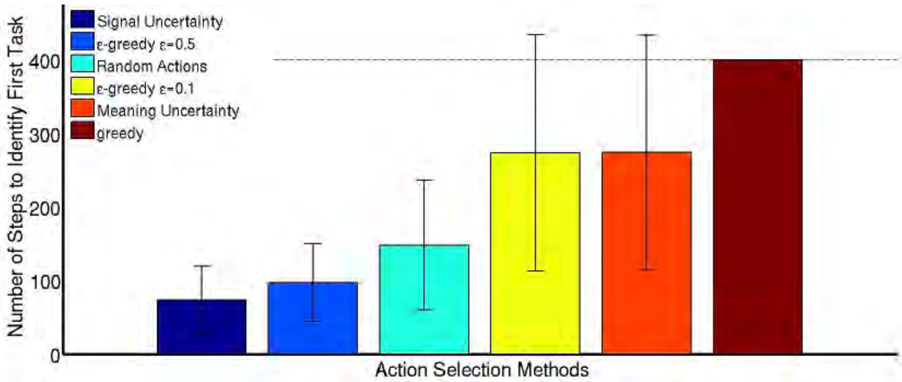


Figure 16: Comparison between different exploration methods. Planning wrt. uncertainty in noth task and signal space is the most efficient method

4.5.10 PyQMC: Python library for Quasi-Metric Control

Functional Description PyQMC is a python library implementing the control method described in [36]. It allows to solve discrete markovian decision processes by computing a Quasi-Metric on the state space. This model based method has the advantage to be goal independent and thus can produce a policy for any goal with relatively few recomputation. New addition to this method is the possibility of online learning of the transition model and the Quasi-Metric.

- Participant: Steve Nguyen
- Contact: Steve Nguyen
- URL: https://github.com/SteveNguyen/pyqmc

4.5.11 Meka robot plateform enhancement and maintenance

Functional Description Autonomous human-centered robots, for instance robots that assist people with disabilities, must be able to physically manipulate their environment. There is therefore a strong interest within the FLOWERS team to apply the developmental approach to robotics in particular to the acquisition of sophisticated skills for manipulation and perception. ENSTA-ParisTech has recently acquired a Meka (cf. 17) humanoid robot dedicated to human-robot interaction, and which is perfectly fitted to this research. The goal of this project is to install state-of-the-art software architecture and libraries for perception and control on the Meka robot, so that this robot can be jointly used by FLOWERS and ENSTA. In particular, we want to provide the robot with an initial set of manipulation skills.
The goal is to develop a set of demos, which demonstrate the capabilities of the Meka, and provide a basis on which researchers can start their experiments.

The platform is evolving as the sofware (Ubuntu, ROS, our code) is constantly updated and requires some maintenance so less is needed for later. A few demos were added, as the hand shaking demo, in which the robot detects people via kinect and initiates a hand shake with facial expressions. This demo has been used to setup a bigger human robot interaction experiment, currently tested on subjects at Ensta (cf. 18). Finally, we've seen that the robot itself also needs some maintenance; some components broke (a finger tendon), a welding got cold (in the arm) and a few cables experienced fatigue (led matrix and cameras) (cf. 19).

- Participants: Antoine Hoarau, Freek Stulp and David Filliat
- Contact: David Filliat

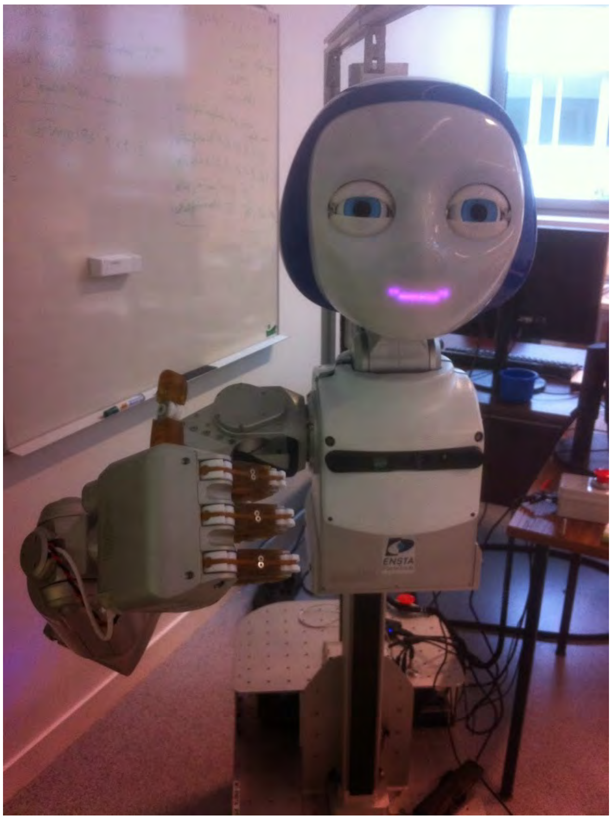


Figure 17: The Meka robot plateform acquired by ENSTA ParisTech

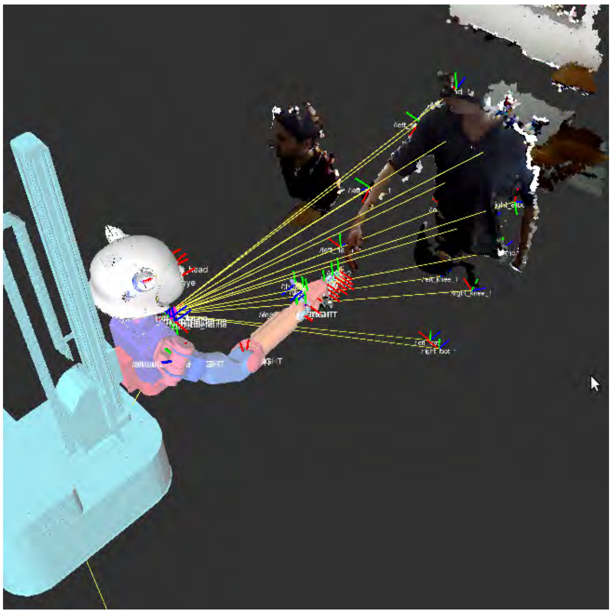


Figure 18: Hand shake demo visualized on Rviz (ROS)

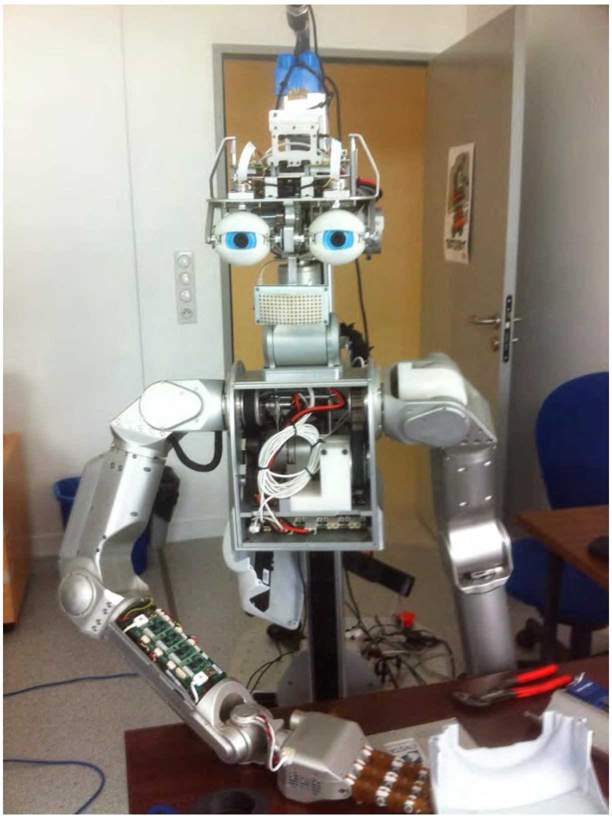


Figure 19: Maintenance is required on the robot

4.5.12 RLPark: Reinforcement Learning Algorithms in JAVA

Functional Description RLPark is a reinforcement learning framework in Java. RLPark includes learning algorithms, state representations, reinforcement learning architectures, standard benchmark problems, communication interfaces for three robots, a framework for running experiments on clusters, and real-time visualization using Zephyr. More precisely, RLPark includes:

- Online Learning Algorithms: Sarsa, Expected Sarsa, Q-Learning, On-policy and off-policy Actor-Critic with normal distribution (continuous actions) and Boltzmann distribution (discrete action), average reward actor-critic, TD, TD(λ), GTD(λ), GQ(λ), TDC
- State Representations: tile coding (with no hashing, hashing and hashing with mumur2), Linear Threshold Unit, observation history, feature normalization, radial basis functions
- Interface with Robots: the Critterbot, iRobot Create, Nao, Puppy, Dynamixel motors
- Benchmark Problems: mountain car, swing-up pendulum, random walk, continuous grid world

An example of RLpark running an online learning experiment on a reinforcement learning benchmark problem is shown in Figure 20.

RLPark was started in spring 2009 in the RLAI group at the university of Alberta (Canada) when Thomas Degris was a postdoc in this group. RLPark is still actively used by RLAI. Collaborators and users include Adam White, Joseph Modayil and Patrick Pilarski (testing) from the University of Alberta.

RLPark has been used by Richard Sutton, a professor and iCORE chair in the department of computing science at the University of Alberta, for a demo in his invited talk *Learning About Sensorimotor Data* at the Neural Information Processing Systems (NIPS) 2011 http://webdocs.cs.ualberta.ca/~sutton/Talks/Talks.html#sensorimotor. Patrick Pilarski used RLPark for live demos on television (Breakfast Television Edmonton, CityTV, June 5th, 2012) and at TEDx Edmonton on Intelligent Artificial Limbshttp://www.youtube.com/watch?v=YPc-Ae7zqSo. So far, RLPark has been used in more than a dozens of publications (see http://rlpark.github.com/publications.html for a list).

RLPark has been ported to C++ by Saminda Abeyruwan, a student of the University of Miami (United States of America). The Horde architecture in RLPark has been optimized for GPU by Clément Gehring, a student of the McGill University in Montreal (Canada).

Future developments include the implementation of additional algorithms (the Dyna architecture, back propagation in neural networks, ...). A paper is under review for the JMLR Machine Learning Open Source Software. Documentation and tutorials are included on the RLPark web site. RLPark is licensed under the open source Eclipse Public License.

- Contact: Thomas Degris
- URL: http://rlpark.github.com

4.5.13 Zephyr: Realtime Visualization in JAVA

Functional Description Zephyr is a software to visualize numeric variables and data structure in real time and at different time scale. Zephyr is practical because it requires only minimal changes in the code: it uses Java reflexivity to automatically detect variables in the code to monitor and data structure with an associated dedicated view. Zephyr can easily be extended with new plugins because it is based on the popular Eclipse Rich Client Platform. Consequently, Zephyr takes advantage of an already existing and fully operational Eclipse plugins for many of its functionalities. Finally, Zephyr is distributed with a Java python virtual machine named Jython and a lisp implementation named Clojure. An example of a Zephyr screen is shown in Figure 21.

Zephyr was started in fall 2009 in the RLAI group at the university of Alberta (Canada) when Thomas Degris was a postdoc in this group. Zephyr is still actively used by RLAI. Users include Adam White, Joseph Modayil and Patrick Pilarski from the University of Alberta. Zephyr has

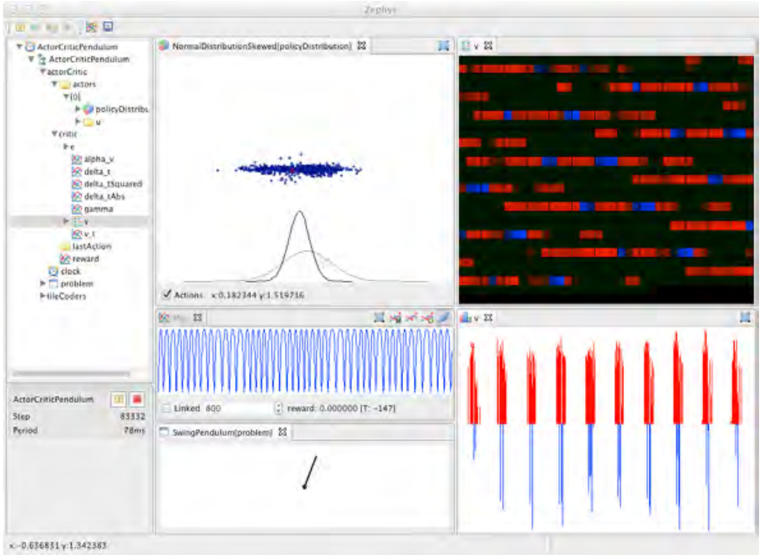


Figure 20: An example of an experiment in RLPark. Zephyr displays two views of a learned weight vector, an animation of the problem, the current policy distribution learned by the algorithm and the reward obtained by the algorithm. Videos are available at: http://rlpark.github.com.

been registered on the Eclipse marketplace since October 2011. Documentation about Zephyr is included on its website. Zephyr is licensed under the open source Eclipse Public License.

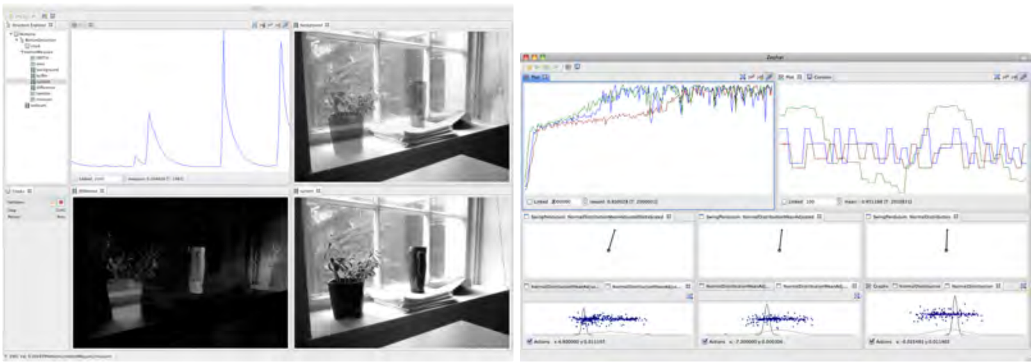


Figure 21: Left: Zephyr showing the different steps of a video processing pipeline in real-time. Right: Zephyr showing different data structure and variables of a reinforcement learning agent at different time scale. A video is available at: http://zephyrplugins.github.com.

- Contact: Thomas Degris
- URL: http://zephyrplugins.github.com

5 Funding

National initiatives

ANR MACSi, ANR Blanc, Coordinator: ISIR/UPMC (Olivier Sigaud), Partners : INRIA, ENSTA ParisTech, Gostai. Nov 2012 - Oct 2013, 232 122 euros, The MACSi project is a developmental robotics project based on the iCub humanoid robot and the Urbi open source software platform. The goal is to develop a software architecture for efficient motor and perceptual representation development. http://macsi.isir.upmc.fr/

Ecole du Code, PIA, http://www.ecoleducode.net/, 2016-2017. This project provides teachers and animators formations and learning games to initiate young people to computer science and robotics. Inria Flowers got 75 keuros funding.

ROBOT POPULI, FUI, Coordinator: Awabot, Partners : ARTEFACTS STUDIO, LIRIS, ENSTA ParisTech, GAMAGORA (Université Lyon 2), march 2012 may 2015, funding 103 600 euros. The project aims to investigate, prototype, and test new applications and interactions between the robot and the user to move from niche markets to the general public.

ROMEO 2, PSPC, Coordinator: Aldebaran Robotics, Partners : ALL4TEC, Inria, CNRS, VOXLER, SPIROPS, ISIR, UVSQ, CEA LIST, ENSTA ParisTech, STRATE COLLEGE, TELECOM PARISTECH, ASSOCIATION APPROCHE, from 2012 to 2016, funding 500 312 euros. This project aims at developing a humanoid robot for assisting people. The contribution of FLOWERS and ENSTA ParisTech are in the area of human-robot interaction, learning by demonstration, perception and semantic mapping.http://projetromeo.com/

PERSEVERONS, PIA, 2016-2019. This projects aims at studying the educational impact of educational robotics kits in high-schools. Inria got a funding of 146 keuros.

PEPS CNRS Grant PY Oudeyer and M Lopes collaborated with Aymar de Rugy, Daniel Cattaert and Florent Paclet (INCIA, CNRS/Univ. Bordeaux) about the design of myoelectric robotic prostheses based on the Poppy platform, and on the design of algorithms for co-adaptation learning between the human user and the prosthesis. We received 10 keuros funding.

European projects

ERC EXPLORERS, ERC Starting Grant, Coordinator: Pierre-Yves Oudeyer, Dec 2009 - Nov 2014, 1.5 million euros. EXPLORERS proposes to focus on the developmental processes that give rise to intelligence in infants by re-implementing them in machines. Framed in the developmental/epigenetic robotics research agenda, and grounded in research in human developmental psychology, its main target is to build robotic machines capable of autonomously learning and re-using a variety of skills and know-how that were not specified at design time, and with initially limited knowledge of the body and of the environment in which it will operate.

3rd HAND (Semi-Autonomous 3rd Hand), FP7, Coordinator: Inria, Partners: Technische Universitaet Darmstadt (Germany), Universitaet Innsbruck (Austria), Universitaet Stuttgart (Germany). Oct 2013 - Sept 2017, 618 400 euros. The main contributions of this project will be the scientific principles of semi-autonomous human-robot collaboration, a new semi-autonomous robotic system that is able to: i) learn cooperative tasks from demonstration; ii) learn from instruction; and iii) transfer knowledge between tasks and environments. http://www.3rdhandrobot.eu

DREAM (Deferred Restructuring of Experience in Autonomous Machines): H2020, Coordinator: UPMC, Partners: Armines (ENSTA ParisTech), Queen Mary University London (England), University of A Coruna (Spain), Vrije University Amsterdam (Holland). Jan 2015 - Dec 2018, funding : 512 480 euros. DREAM is a project dedicated to bootstrapping development by making a robot discover the features of its environment and how it can interact with it. It is focused on the discovery of objects through interaction, on the acquisition of motor skills required to interact with them and on their consolidation that allows transfer and generalization to new domains. http://www.robotsthatdream.eu

IGLU (Interactive Grounded Language Understanding) CHIST-ERA, Coordinator: University of Sherbrooke, Canada, Partners: INRIA Bordeaux, France, University of Mons, Belgium, KTH Royal Institute of Technology, Sweden, University of Zaragoza, Spain, University of Lille 1, France, University of Montreal, Canada. Oct 2015 - Sept 2018, 150.800 euros. Language is an ability that develops in young children through joint interaction with their caretakers and their physical environment. Through a developmental approach where knowledge grows in complexity while driven by multimodal experience and language interaction with a human, we propose an agent that will incorporate models of dialogues, human emotions and intentions as part of its decision-making process. http://iglu-chistera.github.io/

Industrial contracts

Advanced platform for Urban Mobility (PAMU); 2013 2016, 90 000 euros, We developed for Renault a path planning and decision making software for a autonomous valet parking.

ITWell, KidBreath project A CIFRE PhD grant from the e-Health company ITWell fully funds a PhD thesis on the study of personalization algorithms effects in the context of serious games for asthmatic children. Funding: 150 keuros.

Development of an Contextual electronic copilot for driving assistance: Financing of the CIFRE PhD grant of Alexandre Armand by Renault SAS with the goal of developing an Contextual electronic copilot for driving assistance based on the learning of the behavior of the driver. Funding : 150 keuros.

Inria Project Labs, Exploratory Research Actions and Technological Development Actions

CARRoMan, ADT, november 2012 november 2014, funding for 2 years of research engineer. The goal of this ADT is to install state-of-the-art software architecture and libraries for perception and control on the Meka robot at ENSTA ParisTech, so that this robot can be jointly used by FLOWERS and ENSTA. In particular, we want to provide the robot with an initial set of manipulation skills. The engineer will develop a set of demos, which demonstrate the capabilities of the Meka, and provide a basis on which researchers can base their experiments.

Open Poppy See Poppy Education project below.

Associated teams and other international projects

NeuroCuriosity, joint team in neurosciences, with University of Columbia (United States) - Jacqueline Gottlieb, started in 2013. We aim to develop a novel unified biological and computational theory, which explains curiosity in the domain of visual exploration and attention as a deliberate decision motivated by learning progress. This theory will build and improve upon pioneer computational models of intrinsic motivation elaborated in developmental robotics, and be empirically evaluated in the context of visual exploration in monkeys through behavioral and brain imaging techniques. Funding: 45 keuros.

LoCoRoS, Proteus 2015, Coordinator: ENSTA ParisTech, 2015 2016, funding 10 000 euros, Collaboration with Andrej Gams and Rok Vuga of the Josef Stefan Institute, Ljubljana, Slovenia. Funded by the "Programme Proteus 2015" for cooperations between France and Slovenia.

Other funding

Poppy Education, Feder - Région Aquitaine, Coordinator: INRIA FLOWERS, January 2014 - December 2017, Funding: 1 million euros (co-funded by Feder/EU Commission, Region Aquitaine and Inria). Poppy Education aims to create, evaluate and disseminate pedagogical kits “turnkey solutions” complete, open-source and low cost, for teaching computer science and robotics.It is designed to help young people to take ownership with concepts and technologies of the digital world, and provide the tools they need to allow them to become actors of this world, with a considerable socio-economic potential.

KidLearn A Conseil Régional d’Aquitaine Project Coordinator: INRIA Flowers, 2015 2018, funding : 50 000 euros. This project will fund 50% of a 3 years PhD student and aims at elaborating algorithms and software systems to help humans learn efficiently, at school, at home or at work, by adapting and personalizing sequences of learning activities to the particularities of each individual student.

Curiosity and visual attention: Financing of the CIFRE PhD grant of Celine Craye by Thales S.A. with the goal of developing a mechanism of visual attention guiding the exploration of a robot. Funding : 150 keuros.

Ecole Normale Supérieure Two PhD students of the team obtained full PhD grants from Ecole Normale Supérieure of Lyon and Cachan, total funding is 200 keuros.

Inria CORDIS The Flowers team obtained one postdoc and one full Phd CORDIS grant, total funding: 200 keuros.

Comacina Capsule Creative Art/Science project and Idex/Univ. Bordeaux, funding XXX euros. The Comacina project explored the role of movements and light in expressing emotions: http://comacina.org. This project was implemented through several residencies during the year, and several performances at various cultural places in Aquitaine, including at Pole Evasion in Ambares-et-Lagrave.

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