IM-CLeVeR:
Intrinsically Motivated Cumulative Learning Versatile Robots

Web: www.im-clever.eu **Coordinator contact:** gianluca.baldassarre@istc.cnr.it

Project summary

IM-CLeVeR aims to develop a new methodology for designing robots controllers that can: (1) cumulatively learn new efficient skills through autonomous development based on intrinsic motivations, and (2) reuse such skills for accomplishing multiple, complex, and externally-assigned tasks. During skill-acquisition, the robots will behave like children at play which acquire skills autonomously on the basis of "intrinsic motivations". During skill-exploitation, the robots will exhibit fast learning capabilities and a high versatility in solving tasks defined by external users due to their capacity of flexibly re-using, composing and re-adapting previously acquired skills.

This overall goal will be pursued investigating three fundamental scientific and technological issues: (1) the mechanisms of abstraction of sensory information; (2) the mechanisms underlying intrinsic motivations, e.g. "curiosity drives" that learn to focus attention and learning capabilities on "zones of proximal development"; (3) hierarchical recursive architectures which permit cumulative learning. The study of these issues will also be fuelled by a reverse-engineering effort aiming at reproducing with bio-mimetic models the results of empirical experiments run with monkeys, children, and human adults. The controllers proposed will be validated with challenging demonstrators based on a single humanoid robotic platform (iCub).

The project will significantly advance the scientific and technological state of the art, both in terms of theory and implementations, in autonomous learning systems and robots. This goal will be achieved on the basis of the integrated work of a highly interdisciplinary Consortium involving leading international neuroscientists, psychologists, roboticists and machine-learning researchers.

Keywords

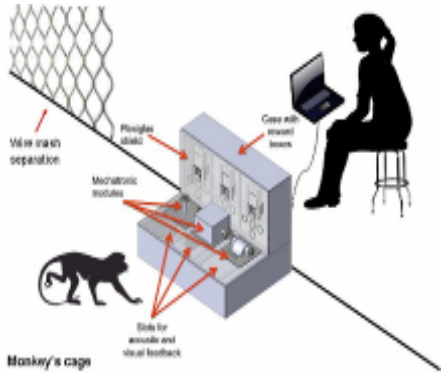
Developmental robotics, autonomous learning, reinforcement learning, action hierarchies, neural networks, novelty detection, developmental/cognitive psychology, brain, dopamine.

Project objectives

- To substantially *increase our knowledge on intrinsically motivated cumulative learning* in organisms through non-invasive experiments with monkeys, children, and human adults.
- To *develop bio-constrained models* (including computer simulations and robotic experiments) reproducing and explaining the findings of the relevant empirical experiments.
- To *develop new machine learning techniques*, architectures, and learning algorithms for the optimal design of cumulative learning robots.
- To *integrate the knowledge* gained with the empirical experiments, the bio-constrained computational models, and the development of machine learning techniques to build robot controllers which exhibit intrinsically motivated cumulative learning in the iCub robot.

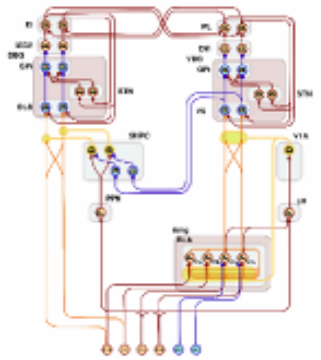
Work performed and main results achieved

In its first year, the project achieved important results in various directions: the definition of innovative experimental paradigms to investigate intrinsically-motivated action learning, the development of bio-constrained models of intrinsic motivations and hierarchical behaviour, the preparation of machine learning architectures for solving complex sensorimotor problems, and the design of integrated architectures to investigate all these issues within the three iCub robots available at the beneficiaries' labs. The most important achievements in these fields are as follows:



Mechatronic board and empirical experiments.

- Development of a new experimental paradigm to investigate learning of action-outcomes and actions performed on a joystick, usable with rats and humans
- Construction of an innovative highly-modular and flexible Mechatronic Board usable with to investigate intrinsically-motivated learning monkeys and humans
- Formulation of new experimental protocols to investigate intrinsically motivated cumulative learning in monkeys, children, human adults, and Parkinsonian patients.

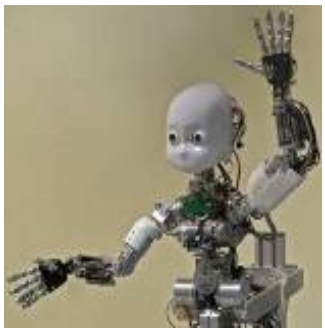


Development of bio-constrained computational models

- Models of extrinsic and intrinsic motivations
- Theory and robotic models of the staged development of sensorimotor skills in children
- Models of the brain dopamine system and basal ganglia mechanisms at the basis of intrinsically motivated learning of actions
- Models of various brain systems at the basis of intrinsically motivated cumulative learning, e.g. basal ganglia-cortical loops and cortico-cortical pathways implementing habits and goal-directed behaviour

Development of machine learning models

- Novel system for visual perception and abstraction
- Novelty detection algorithms based on static images and optical flow
- Novel hierarchical reinforcement learning models
- Innovative predictive models of robots' body and environment
- Information-theory based approaches to intrinsic motivations
- Sofware-hardware infrastructures for the implementation of integrated demonstrators



The integration work and the robotic demonstrators

- Blueprint of a machine-learning robot controller capable of: (a) developing new actions on the basis of intrinsic motivations (b) re-using and assembling them to pursue new goals
- Blueprint of a bio-constrained integrated architecture capable of (a) learning actions/action-outcomes based on intrinsic motivations (b) re-using the acquired actions based on extrinsic motivations

Potential impact and use: Science

IM-CleVeR directly contributes to the impact of the ICT Workprogramme, Challenge 2 (Cognitive Systems, Interaction, Robotics) through the development of a *novel robotic design methodology* that permits to *develop robots that exhibit robust and versatile behaviour*.
The project delivers a number of key innovations:

- A *foundational theoretical scientific and technological knowledge* on intrinsically motivated cumulative learning and Autonomous Mental Development.
- *A methodology for developing robots capable of learning new skills in an unsupervised and open-ended fashion*. This methodology is based on the integration of state-of-the-art machine learning techniques and biologically-constrained computational mechanisms.
- *New algorithms for supporting learning based on intrinsic motivations*, such as algorithms based on novelty detection and competence acquisition. This gives the robots *full cognitive and emotional autonomy*, namely little need for re-programming when passing from one task to another.
- *Hierarchical architectures for robot control*, e.g. based on neural networks, which support: (a) cumulative learning of skills while minimising catastrophic interference; (b) learning of action outcomes and the association of skills to such outcomes; (c) composition of skills to accomplish new goals.
- *Two novel experimental paradigms to investigate intrinsically motivated learning in monkeys, children and humans*: (a) one based on a very flexible mechatronic board containing curiosity-eliciting objects with various types of perceptual features, affordances, and visual/sound feedbacks; (b) one based on a joystick which controls a screen cursor to which various types of effects can be associated.

Potential impact and use: Technology

The Work Program aims to "extended capabilities of people to perform routine, dangerous or tiring tasks in previously inaccessible, uncharted or remote spaces; saving critical time in emergencies or hazardous situations". Although *IM-CleVeR* does not aim to directly produce any of this applications, the *results it is producing in terms of robot design methodology have a significant impact on future autonomous robots technology*. Indeed, the capability to autonomously focus on more "interesting" events and objects and to develop a repertoire of skills for *dealing with unstructured situations* represents a breakthrough in robotic technologies as leads to *enhanced adaptability, behavioural flexibility, and dependability of robots*.

These features of robots are necessary for a *massive exploitation of autonomous robotics to accomplish everyday routines* for which robots have to autonomously learn several different tasks. Indeed, the *kitchen scenario* used to test the robots of the project was purposefully designed with this long-term applicative goal in mind. The insights produced by the project are equally important for developing the future robots capable of *acting in dangerous situations or inaccessible remote spaces*. Indeed, in these situations *external instructions are very limited* and robots have to be able to adapt and re-adapt autonomously.

Potential impact and use: Socio-economic

The robots developed in the project can be used to *investigate the best cognitive and motivational conditions that increase the steepness of the learning curve of particular skills*. Indeed, the developed systems are strongly related to the way children learn and so can furnish important insights on the underlying processes. The project also contributes to the development of a new generation of robots that can be used in for *edutainment*, namely robots capable of generating continuously novel interactions, and for *rehabilitation*, for example to facilitate learning of complex motor skills by children affected by neurodevelopmental disorders such as *autism* (autistic subjects interact easily with robots due to their high predictability).

The exploitation of *cognitive science for producing intelligent robots is a novel industry field*, and no leadership has still been established among countries. This is the time to boast European research in this sector to achieve such *leadership*. There are *good premises for this*: (a) Europe has a leadership in cognitive sciences (see the EU Cognition Unit); (b) Europe has a strong position in the industrial field of precision mechanics (see the successful experience of the iCub robot). To acquire a full leadership, however, both financial and intellectual resources are needed. The Cognition Unit initiatives fulfil the first precondition. IM-CLeVeR gives an important contribute to fulfil the second precondition by contributing to develop a new *robot design methodology for producing autonomous robots*.

Beneficiaries of the project

Beneficiary Number	Beneficiary name	Beneficiary short name	Country
1 Coordinator	**Consiglio Nazionale delle Ricerche,** **Istituto di Scienze e Tecnologie della Cognizione:** 1.1 Laboratory of Computational Embodied Neuroscience *Coordinator*/Team Leader: *Gianluca Baldassarre* 1.2 Unit of Cognitive Primatology Team Leader: *Elisabetta Visalberghi*	CNR-ISTC-LOCEN CNR-ISTC-UCP	Italy
2	**Universita' Campus Bio-Medico** 2.1 Lab. of Biomedical Robotics and Biomicrosystems Team Leader: *Eugenio Guglielmelli* 2.2 Laboratory of Developmental Neuroscience Team Leader: *Flavio Keller*	UCBM-LBRB UCBM-LDN	Italy
3	**University of Sheffield,** **Department of Psychology** Team Leader: *Peter Redgrave*	USFD	United Kingdom
4	**Goethe University,** **Frankfurt Institute for Advanced Studies** Team Leader: *Jochen Triesh*	FIAS	Germany
5	**University of Ulster,** **School of Computing and Intelligent Systems** Team Leader: *Martin T. McGinnity*	UU	United Kingdom
6	**Aberystwyth University,** **Department of Computer Science** Team Leader: *Mark Lee*	AU	United Kingdom
7	**Istituto Dalle Molle per l'Intelligenza Artificiale,** **Scuola Univ. Profes. della Svizzera Italiana** Team Leader: *Juergen Schmidhuber*	IDSIA- SUPSI	Switzerland

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Machine learning, autonomous robotics, information-theory:
Richard Sutton, Frederic Kaplan, Pierre-Yves Oudeyer, Max Lungarella, Daniel Polani

Legal/administrative details of the project

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