Project IST-004370

RobotCub

Development of the iCub Cognitive Humanoid Robot

Instrument: Integrated Project
Thematic Priority: IST – Cognitive Systems

Fifth Periodic Activity Report

Months 49-65

Period covered from **01/09/2008** to **31/1/2010**

Date of preparation: **11/12/2009**

Start date of project: **01/09/2004**

Duration: **65 months**

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Project coordinator organization name: **University of Genoa, DIST – LIRA-Lab**

Revision: **1.0**

1. Overview

RobotCub is an Integrated Project funded by European Commission through its Cognitive Systems and Robotics Unit (E5) under the Information Society Technologies component of the Sixth Framework Programme (FP6). The project was launched on the 1st of September 2004 and ran for a total of 65 months. The consortium is composed of 11 European research centres and is complemented by three research centres in the USA and three in Japan, all specialists in robotics, neuroscience, and developmental psychology. The non-European partners[1] have a consulting role.

The project has two main goals: (1) to create a new advanced humanoid robot – the iCub[2] – to support Community research on embodied cognition, and (2) to advance our understanding of several key issues in cognition by exploiting this platform in the investigation of cognitive capabilities.

RobotCub is a highly interdisciplinary teamwork-driven project: it depends crucially on the many inputs of all eleven of its partners: from neuroscience and developmental psychology, through computational modelling, computer science, and robotics, to human-robot interaction. The total funding for the project is €8.5 million, a significant component of which (approximately 25%) is targeted at providing up to eight[3] copies of the iCub cognitive humanoid robot for the research community at large.

The iCub itself is a 53 degree-of-freedom humanoid robot of the same size as a three/four year-old child. It can crawl on all fours and sit up. Its hands allow dexterous manipulation and its head and eyes are fully articulated. It has visual, vestibular, auditory, and haptic[4] sensory capabilities. The iCub is an open systems platform: researchers can use it and customize it freely[5]. It is intended to become the research platform of choice, with people being able to exploit it quickly and easily, share results, and benefit from the work of other users.

Over the past seventeen months, the principal objectives (called specific objectives – SO) for the period have been substantially achieved:

> **SO-1: A timeline description of human infants' cognitive development based on recent and well documented experimental results.** This is likely to be made into a book published, for example, in the Cognitive Systems Monographs series (COSMOS, Springer). A new version of the Cognitive Architecture suitable for implementation has been created.
>
> **SO-2: The finalization of the complete design, fabrication, assembly, test, and documentation of the iCub and its duplication in a number of copies for the winners of a competitive call.**

[1] Formally, non EU partners aren't partners in the contractual sense. They were invited to RobotCub meetings and activities with a consulting role in the recognition of their scientific excellence in some of the topics of the RobotCub project.
[2] CUB stands for *Cognitive Universal Body*.
[3] Seven platforms were finally awarded to research institutions worldwide, all delivered at the moment of writing. Two additional platforms were built and awarded to the Consortium following the Y1 reviewers' recommendations. Two platforms are also available in Genoa, the initial prototype and a copy realized on IIT internal funding.
[4] Under development (see FP7 project Roboskin, FP7-IST-231500).
[5] The iCub is freely licensed under the GNU General Public Licence.

Although amenable to improvements (currently a new version is under study and initial design stage), the iCub is in a state whereby multiple copies have been built (15 at the moment of writing) or are planned (5 more in the production line), several heads or other body parts have been also built (3) or are planned (3 more).

SO-3: The implementation of a set of cognitive abilities in the iCub. Several basic cognitive abilities have been implemented on the iCub following a general sketch of a cognitive architecture. These include: reaching, grasping, affordance learning, crawling, attention, basic vision (stereo, motion), memory (episodic and procedural), some interaction and imitation skills. All Workpackages have their work on the iCub following the iCub software standards. There were four subgoals as detailed below:

a. The ability of learning and exploiting object affordances in order to correctly manipulate objects on the basis of the goal of the experiment.
b. The ability of understanding and exploiting simple gestures to interact socially.
c. The ability of learning new manipulation skills and new communicative gestures by correctly interpreting and imitating the gestures of a human demonstrator.
d. The ability to crawl, sit up, and keep the upper torso and head stable when reaching.

We are confident to say that tasks (a), (b), and (d) are at a good level of implementation and integration. Task (c) is somewhat more fragmented.

SO-4: Results of the testing of new technologies. Technology evaluation is continuing. While this cannot influence the current realization of the iCub's, it is possible to start planning a second design iteration with some technological improvements: e.g. joint-level torque control, smoother trajectory generation, skin sensing, custom motors, and better camera/lenses, new control electronics. This is currently under design in good part thanks to IIT internal funding.

SO-5: Community building has continued at a good pace. The iCub middleware for example is being used to develop robot control software or in general to support cognitive systems work in several laboratories outside the RobotCub consortium. More iCub's are under construction. The total count by mid 2010 will be of 20 (complete platforms) plus several partial realizations. A form of *association* or *foundation* (the legal form is probably going to be a European Interest Group) for managing the iCub software, hardware, to take decisions and integrate further work is going to be created. We formed contacts with other Open Source developers as e.g. Willow Garage (http://www.willowgarage.com) and AIST Open RTM (http://www.is.aist.go.jp/rt/OpenRTM-aist/html-en/). Integration with Orocos (http://www.orocos.org/) has been also started by independent developers.

Most significant deliverables

Deliverable number	Title	Description
D2.1	A Roadmap for the Development of Cognitive Capabilities in Humanoid Robots.	This is the final update of the Cognitive Roadmap. This deliverable is a written report.
D2.2	Software Implementation of the iCub Cognitive Architecture	This deliverable is a report (manual) and demo (software) of the iCub Cognitive Architecture, release

	(version 2.0).	2.0 (release 1.0 was delivered at M48).
D3.6	Software implementation of the phylogenetic abilities specifically for the iCub & integration in the iCub Cognitive Architecture.	This deliverable collects all contributions to the D2.2 from Workpackage 3 (sensorimotor coordination). In practice, this is a report and demo (manual and software) of the experiments on sensorimotor coordination and elements of the Cognitive Architecture as identified in D2.1. This deliverable has been made into a Wiki page which contains links to the software modules/applications (running on the iCub and committed to the iCub repository) and links to technical papers and videos.
D3.7	Results from Electrophysiological study of human sensorimotor representations.	This deliverable is a report on the experiments concerning the study of human sensorimotor representation. Thanks to UNIFE, RobotCub had the unique chance of access data of electrophysiological recording in humans during surgery. This deliverable reports about these studies.
D3.8	Demo of the iCub crawling and switching to a sitting position.	This is a demo of the iCub crawling controllers.
D4.1	Results of experiments on affordant behaviours.	This deliverable is made of two components: a report on the experiments on learning and detecting affordances, and the demo of the same experiments on the iCub.
D4.2	Software for the iCub & integration in the iCub Cognitive Architecture.	This deliverable item is the software contribution of Workpackage 4 to the Cognitive Architecture (see D2.2).
D5N.1	Imitation and communication for the iCub.	This report of the new Workpackage (WP5N) describes the experiments on imitation and communication.
D5N.2	Imitation and communication on the iCub.	This is the demonstration of the experiments described in D5N.1.
D5N.3	Imitation and communication software release for the iCub.	This is the software contribution of Workpackage 5N to the Cognitive Architecture described in D2.2 and represents also the demo of D5N.2 and reported in D5N.1.
D7.5	Status of the platform: major changes, debugging activities, problem report.	A description of the iCub final modifications (new versions, improvements, etc.).
D8.5	Robot Documentation.	The latest version of the iCub manual which is available online (Wiki pages). This is the ultimate collection of documents describing hardware and software of the iCub.
D9.2	Material produced for the training activities.	Description of the activities organized for training. RobotCub has organized its annual Summer School

		and a number of additional training events especially to iCub owners.
D9.3	Progress report on Internationalization activities.	Dissemination about the iCub and RobotCub has been solid during the last period of the project. This is a report of the activities.

All deliverables have been completed.

Legend

For convenience we report here the list of partners and adopted short names.

Partner number	Short name	Full name
1	UGDIST	University of Genoa, DIST, IT
2	SSSA	Scuola Superiore S. Anna, IT
3	UNIZH	University of Zurich, CH
4	UNIUP	University of Uppsala, SE
5	UNIFE	University of Ferrara, IT
6	UNIHER	University of Hertfordshire, UK
7	IST	Istituto Superior Tecnico, PT
9	EPFL	Ecole Polytechnique Federal de Lausanne, CH
10	TLR	Telerobot Ocem Srl, IT
12	IIT	Italian Institute of Technology, IT
13	USFD	University of Sheffield, UK

Partner 8 (Univ. of Salford) left the Consortium in favour of partner 13. Partner 11 EBRI left the Consortium after year 2 (no expenditure).

RobotCub papers are marked in yellow and are available for download from:
http://www.robotcub.org/misc/review5/papers/papers.html
they contain full technical details of the experiments are complete results.

Key results

Although the overall timing of the project was very tight, the project is substantially on schedule and the major milestones have been met. In particular, (M4.1) the Open Call has been completed (7 robots delivered), (M4.2) the iCub Open Source is “self supporting” being used outside the iCub consortium and by a larger group of users than originally planned for (though hoped), and (M4.3) the Consortium released a new version of the iCub Cognitive Architecture software.

The following are a selection of highlight of the results achieved by the project over the past 17 months.

Many more achievements are detailed in Section 2.

1. More than 70 papers have been published (or are currently submitted or accepted) during the last period; this number is approximately similar to the previous period. A full list is provided in Section 5 and available for download from the URL:

   http://www.robotcub.org/misc/review5/papers/papers.html
2. 7 copies of the iCub have been built for the Open Call, 4 copies for the partners, several other parts (heads) also made available inside the Consortium.
3. iCub v1.1 have been designed and standardized as the final version at the end of RobotCub. This includes: force/torque sensors, full body covers, additional electronics (hand position sensors), some rewiring, noise reduction in position measurements, and a certain number of small modifications/improvements. Currently, 3 robots (2 at IIT and 1 outside IIT) have been updated to v1.1. The remainder of the Open Call robots is at version 1.0. New robots will be built directly at version 1.1 and possibly existing robots upgraded (as for the ITALK project robots). Robot versions are described later in WP7.
4. New documentation structure on the RobotCub Wiki in the form of a manual. This will include all documentation required to duplicate, assemble, install and run the iCub and includes both hardware and software (D8.5). This has been updated consistently since last period also because of standardization of the production procedures.
5. Porting of all subsystems developed in the various WPs into the iCub making all software fully compatible. More integration has been achieved as per the reviewers’ request. Especially, with respect to the role of attention in the Cognitive Architecture, integration between robotics and neuroscience has progressed substantially.
6. It was decided to extend the Open Call to one more winner (Urbana-Champaign).
7. A new release of the Roadmap of the Development of Cognitive Capabilities in Humanoid Robots (D2.1) has been prepared; this document will form the seed of a book published by Springer.
8. iCub was made to reach and grasp objects reliably (with certain limitations), this now connects smoothly with the research on learning of affordances.
9. Zero-force control can be demonstrated on the iCub using the installed force-torque sensors.
10. New experiments on infants and adults have been developed looking at reaching, objects, the understanding of actions and communication behaviours.
11. Electrophysiological recording in humans have been performed.

12. The iCub has been upgraded in several ways. Versioning has been defined for the iCub mechanics/electronics. A new release (v2.0) with several advanced features is in a later stage of mechanical design.
13. Some investigation on the “fitness” of the iCub for bipedal walking has been completed. This helps in improving the design of the new release (v2.0). In particular, a gait model for the iCub was developed.
14. Effect of force in the interpretation of observed actions has been assessed in humans by using TMS. Also, a TMS experiment shows the involvement of the primary motor cortex (M1) in the perception of speech.
15. Imitation behaviours can be shown on the iCub. This is one of the demos at the review meeting.
16. The Interaction History Architecture (IHA) has been used in a new experiment showing human-robot interaction on the iCub. New modules and sensory processing have been added.
17. Sensorized fingertips are at a later stage of integration on the iCub (v1.2).
18. An improved PC104 I/O card has been designed with advanced characteristics (to support further development on the iCub). Current control on the iCub electronics has been tested (by small modifications of the existing electronics, this can be retro-fitted to the existing cards).
19. A new XML standard has been defined to support the standardization of iCub applications made of several modules. An easy-to-use GUI is automatically generated from such applications helping the user in quickly starting up the iCub.
20. The iCub appeared on several important dissemination and media events including among others “Nature”, ICT in Lyon, IJCAI in the US, Futuris on Euronews and a documentary film “Plug and Pray”.

2. Contribution to the research field

Relation to the Current State-of-the-Art

To the best of our knowledge, the iCub cognitive humanoid robot is at the forefront of research in developmental robotics. The empirical work on cognitive neuroscience and robotics that carried out by the partners is leading edge research. Together, these efforts have led to approximately 70 publications in the past period.

We believe that RobotCub is truly an exceptional project for many reasons among which:

- The creation of a developmental roadmap of human development; while this can potentially transform into a book, the Deliverable 2.1 contains already a full-fledged program of empirical research that may keep scientists busy for many years to come. This description of human development stresses the role of prediction into the skilful control of movement: development is in a sense the gradual maturation of predictive capabilities;
- The creation of a model of “sensorimotor” control and development which considers “action” (that is, movements with a goal, generated by a motivated agent which are predictive in nature) as the basic element of cognitive behaviours. Experiments with infants and adults have shown that the brain is not made of a set of isolated areas dealing with perception or motor control but rather that multisensory neurons are the norm. Experiments have proven the involvement of the motor system in the fine perception of others’ movements including speech;
- The creation of a computational model of affordances which includes the possibility of learning both the structure of dependences between sets of random variables (e.g. perceptual qualities vs. action and results), their effective links and their use in deciding how to control the robot. Affordances are the quintessential primitives of cognition by mixing perception and action in a single concept (representation);
- The creation of a computation model of imitation and interaction between humans and robots by evaluating the automatic construction of models from experience (e.g. trajectories), their correction via feedback, timing and synchronization. This explores the domain between mere sensorimotor associations and the possibility of true communication between robot and people;
- The design from scratch of a complete humanoid robot including mechanics, electronics (controllers, I/O cards, buses, etc.) and the relative firmware;
- A software middleware (YARP) which is now used even outside the project and given freely to the Open Source community;
- The creation of a community of enthusiastic users and researchers working on testing, debugging and potentially improving the iCub of the future.

To summarize, although much is still to be done to implement the cognitive skills described in our D2.1 (roadmap of human development), we believe RobotCub to be a milestone in cognitive systems research by setting the basis and a solid framework for the community at large and for the first time providing opportunities of solid progress. This is possible because of the opportunity of creating critical mass, using a common robotic platform and common software architecture, with the availability of technical support from an enthusiastic multidisciplinary team of developers, researchers and cognitive scientists. This places Europe at the forefront of research in cognitive systems and robotics, while maintaining truly international collaborations (via the Open Source strategy).

Use of the knowledge generated by the project

The knowledge being generated by the project can potentially be used any time, in the sense of being taken up by third parties in a transparent manner. The RobotCub project is dedicated to the production of free-available open source results licensed under the GNU General Public Licence. Consequently, direct commercial exploitation is possible according to the terms of the license. However, producing the iCub is still a difficult (and expensive) endeavour and consequently direct exploitation can only happen once applications justify the cost.

For the time being, our explicit goal is to make the iCub humanoid robot the platform of choice for empirical research in embodied cognition and, to that end, our focus is on producing industrial grade designs and software, and making them freely available to the community on the RobotCub SVN repository.

In spite of the restrictions of the GPL, several other research projects started using components of our software, in many cases unnoticed by the RobotCub consortium. For example, FP7 projects ITALK adopted the iCub as standard platform and is now actively contributing with an open source simulator. The project URUS used YARP (our middleware) and developed further on it (in particular an XML layer that formally describes applications). The project CHRIS (also FP7) adopted YARP as the basic control structure. The project SEARISE uses a good subset of YARP for controlling a trinocular head. The project ImClever is acquiring three copies of the iCub and will be using YARP.

Some snapshots of our work

Table 1: From left to right, from top to bottom: the iCub at IJCAI, Pasadena, CA (July 2009); the iCub reaching demo being shown at the Genoa's science festival (Oct 2009); two moments at ICT in Lyon (Nov 2008) and two pictures of the iCub manipulating objects at the Summer School (July 2009).

3. Follow up of previous review

Recommendations

There were two recommendations following the 4th review meeting in 2008. The text below is copied verbatim from the 4th review report:

1. *WP 3–6 should wrap up at 54 months with results ready for integration during the final 6 months of the project. Concretely, it is necessary to develop for each of these WPs scientific experiments, carried out on the iCub platform (rather than any other platform), which go beyond the current state of the art. Ideally, there should be clear links to the cognitive development roadmap. (See also recommendation/suggestion 2 in JB's report, annex 11.3.) Modify the project plan (month 48-60 Implementation Plan) to terminate individual research on WP 3–6 in month 54 and redirect the resources to completing the iCub scenarios. (But see recommendation 3 in JB's report, section 11.3, regarding crawling and sitting up behaviours; see also paragraph 3.1 in SW's report, annex 11.4.)*
2. *For the final review, demos should all be on the iCub. WP presentations should address the goals of the work package, how they were met (or not). Partner contributions should be clearly identified and, possibly, quantified (see also JB's report, section 11.3 – 1.3, Final Report and Review).*

Following these recommendations, the RobotCub Consortium set up a new implementation plan, which following also an extension of 5 months, can be summarized into five specific objectives: SO1 to SO5, whose key results were already sketched in the previous sections.

Objectives for the Current Period

In short, our objectives were:

- SO1, Cognitive Architecture definition and human cognitive roadmap
- SO2, Open Call and platform completion
- SO3, implementation of the Cognitive Architecture on the iCub
- SO4, technology monitoring
- SO5, community building

The recommendations call for improving integration of the WP into the Cognitive Architecture and demonstrating this progress by better presentations and demos. This translates into revisiting the Cognitive Architecture (SO1) to improve the chances of implementation on the iCub and consequently concentrating most of the effort onto SO3. Simultaneously, SO2 was directed at the completion of the Open Call and robot improvements complemented by SO4 which monitored the possibilities of including new technologies on the iCub. Finally, SO5 was about increasing and improving the iCub community.

For SO3, we have realized a certain number of demonstrations which include (live) as per the implementation plan:

- Reaching, grasping, affordance understanding and imitation;
- Human-robot interaction;
- Crawling;

And a number of ancillary live demonstrations such as:

- Gazing, memory and prediction;
- Force control on the iCub;

And a few more demonstrations on video/teleconferencing:

- Predictive gaze;
- Human imitation.

These demonstrations aim at showing (together with the technical and scientific reporting) that all the objectives have been achieved. Although, much is still to be done to implement the cognitive skills described in our D2.1 (roadmap of human development), we believe RobotCub to be a milestone in cognitive systems research by setting the basis and a solid framework for the community at large and for the first time providing opportunities of solid progress. This is possible because of the opportunity of creating critical mass, using a common robotic platform and common software architecture, with the availability of technical support from an enthusiastic multidisciplinary team of developers, researchers and cognitive scientists. This places Europe at the forefront of research in cognitive systems and robotics, while maintaining truly international collaborations (via the Open Source strategy).

4. Workpackage progress

WP1 – Management

Management of the Consortium progressed smoothly during the last period since all decisions were substantially defined after the 4th review meeting and the recommendations were particularly clear. There were four formal meetings involving the whole Consortium (January, April, July, November in Pontedera, Lisbon, Sestri Levante and Genoa respectively). In addition several smaller meetings were called for discussing specific software-related issues. In particular, IIT/UGDIST people travelled three times to Lisbon while IIT received several visits by partners including UNIHER, EPFL, SSSA, and USFD. The Summer School as in the past served as a main gathering of RobotCub developers and considerable joint work was initiated or completed there.

IIT has received budget (changing the original plan) to manage some of the Open Call acquisition of mechanical and electronics parts more efficiently. The budget transfer happened from UGDIST. Several other small changes in budget allocations have been made although they will be all settled at the end of the project since there aren't other payments foreseen before the end of the project (the last payment had already happened and distribution of funding consequently).

The coordinator UGDIST has also managed the request for extension (by 5 months) of the project and all communication with the Commission. Further details of the project management are available from the periodic management report (including cost tables and effort).

WP2 – Cognitive Development

Workpackage objectives

In this Workpackage, we study the development of early cognition and how to model the relevant aspects of such process within the boundaries of an artificial system. In particular, we investigate the timeframe of a developmental process that begins to guide action by internal representations of upcoming events, by the knowledge of the rules and regularities of the world, and by the ability to separate means and end (or cause and effect). We study and model how young children learn procedures to accomplish goals, how they learn new concepts, and how they learn to improve plans of actions. This research is strongly driven by studies of developmental psychology and cognitive neuroscience and it will result in a physical implementation on an artificial system.

This Workpackage has developed a conceptual framework that forms the foundation of the RobotCub project. It surveyed what is known about cognition in natural systems, particularly from the developmental standpoint, with to goal of identifying the most appropriate system phylogeny and ontogeny. It explored neuro-physiological and psychological models of some of these capabilities, noting where appropriate architectural considerations such as sub-system interdependencies that might shed light on the overall system organization. It prepared a roadmap that uses the phylogeny and ontogeny of natural systems to define the innate skills with which iCub must be equipped so that it is capable of ontogenetic development, to define the ontogenetic process itself, and to show exactly how the iCub should be trained or to what environments it should be exposed to accomplish this ontogenetic development. Finally, it addressed the creation and implementation of an architecture for cognition: a computational framework for the operational integration of the distinct capabilities and cognitive skills developed in WP3-5N, and investigated the (very challenging) issue of theoretical unification of distinct models.

Active tasks

Task 2.1: Survey of what is known about cognition in natural systems, particularly from the developmental standpoint, with to goal of identifying the most appropriate system phylogeny and ontogeny (Note: this is well under way at present; see von Hofsten's paper on development and D2.1).
Task 2.2: Explore neuro-physiological and psychological models of these capabilities, noting where appropriate architectural considerations such as sub-system interdependencies that might shed light on the overall system organization.
Task 2.3: iCub developmental roadmap: using the phylogeny and ontogeny of natural systems to define the innate skills with which iCub must be equipped so that it is capable of ontogenetic development, to define the ontogenetic process itself, and to show exactly how the iCub should be trained or to what environments it should be exposed to accomplish this ontogenetic development.
Task 2.6: Software implementation of the iCub cognitive architecture.

Progress towards objectives

Task 2.1, 2.2 (see also WP3), 2.3.

The latest version of the "Roadmap of the Development of Cognitive Capabilities in Humanoid Robots" (D2.1, RC_DIST_DV_Deliverable_D2.1.pdf) contains now a set of scenarios to guide the implementation of the Cognitive Roadmap in the iCub. Material was added the sections on Core Abilities: in particular to the sections on Objects, and People. Material was added to the sections on Development of Posture and Locomotion and Development of Reaching and Manipulation (four new subsections on Reaching, Grasping, Bimanual Coordination, and Manipulation). Material was added to the Development of Social Abilities.

Section 17 Empirical Investigations was updated by adding sub-sections to individual aspects of the first three experiments: Looking, Reaching, and Reach and Grasp (Sections 17.1 – 17.3). These sub-titles attempt to convey the chief characteristics of the experiments. Section 15.6, the iCub Cognitive Architecture was updated as follows. Section 15.6.6 Realization of an Essential Phylogeny has been extended and four new sections have been added: Section 15.6.7, Realization of the iCub Cognitive Architecture; Section 15.6.8, Implementation of the Cognitive Architecture; Section 15.6.9, The iCub Cognitive Architecture and the Posner Test; and Section 15.6.10, Future Work. Finally Section 15.7, Co-Determination and Co-Development Revisited, has been deleted.

Finally, an account of the revision history has been added to D2.1. We leave the reader to this document for details.

Task 2.6.

The work this year was devoted to a concerted effort to drive the convergence of the software architecture and the cognitive architecture, the subsequent specification of a revised cognitive architecture, followed by the realization of this architecture as a collection of YARP iCub modules.

These changes were motivated by a re-focusing on the function of cognition, in general, and internal simulation, in particular, to provide capabilities for prediction, explanation, and innovation. In addition, cognitive motivation encapsulated in the systems affective state were made more explicit so that they address curiosity (dominated by exogenous factors), exploration (dominated by endogenous factors), and social engagement (where exogenous and endogenous factors balance). This distinction between the exogenous and the endogenous highlighted the need to modify the attention system to incorporate both factors.

These considerations led to significant changes in the cognitive architecture and a rationalization of the software architecture and the cognitive architecture. This rationalization occurred progressively throughout the year, with changes being consolidated at four project meetings in Pontedera (January 2009), Lisbon (April 2009), Sestri Levanti (July 2009), and Genoa (November 2009). These developments (version 0.4 of the architecture) are documented fully on the iCub wiki (see, e.g., http://eris.liralab.it/wiki/ICub_Cognitive_Architecture).

The rationalization of software and cognitive architectures involved the adaptation and extension of the old software architecture which encapsulated gaze, reaching, and locomotion capabilities into a more comprehensive architecture that incorporated the key components of the original cognitive architecture. This revised cognitive architecture thus became the first iteration of a blueprint for the realization of the cognitive architecture as a set of YARP iCub modules. The term software architecture then reverted to its original meaning as the YARP middleware system.

In the process of this rationalization, a major change in specifying the revised cognitive architecture involved the replacement of the internal simulation area which had been inspired by Shanahan's coupled hetero-associative memories with a new approach based on auto-associative perceptual memory and hetero-associative event memory. These were subsequently re-cast as an episodic memory and a procedural memory.

Task 2.6 includes several modifications to the modules and iCub applications. These take the form of the following applications:

- **attentionDistributed:** the iCub attention system
- **armCartesianController:** iCub reliable reaching module
- **demoAffv2:** affordance based behaviours
- **demoGrasp_IIT_ISR:** reach and grasp objects on a table
- **demoReach_IIT_ISR:** 3D tracking and reaching/pointing
- **drummingEPFL:** reaching & rhythmic movement controller
- **iha:** interaction history modules
- **imitation learning:** imitation learning demos

which constitutes the building blocks of the various demos. It is to be noted that a new set of standards (described in WP8) allows a better "packaging" of applications and therefore we were able to recycle developed software with more reliability across institutions.
The applications are listed at:

http://eris.liralab.it/iCub/dox/html/group__icub__applications.html

These applications in turn run blocks of interacting YARP modules which implement (distributed across various machines) the desired behaviours/capabilities.

UGDIST/IIT

The work at UGDIST and IIT include several changes among which, removal of the following components:

- tracker (to be handled instead by attention/salience sub-system)
- face localization (to be handled instead by attention/salience sub-system)
- hand localization (to be handled instead by attention/salience sub-system)
- sound localization (to be handled by salience module)

and the addition of the following components:

- Exogenous Salience and Endogenous Salience
- Locomotion
- Matching
- Auto-associative memory episodic memory
- Hetero-associative procedural memory
- Affective state
- Action selection

Beginning with the VVV 09 Summer School in Sestri Levante in July 2009, we undertook a substantial effort to realize the revised cognitive architecture as a complete software system comprising an integrated collection of YARP iCub modules.

These modules comprise the following:

- *salience*
- *endogenousSalience (work in progress)*
- *egoSphere*
- *attentionSelection*
- *controlGaze2*
- *episodicMemory*
- *proceduralMemory*
- *crossPowerSpectrumVergence*
- *actionSelection (work in progress)*

- *affectiveState (work in progress)*

The salience, *egoSphere*, *attentionSelection*, and *controlGaze2* modules were developed at IST, Lisbon, and were a key factor in the realization of the initial software architecture (version 0.4 and previous versions).

The remaining modules were developed at UGDIST and IIT, Genoa, during and after the VVV '09 Summer School in Sestri Levante.

In addition, several support modules were developed as part of this implementation effort. These comprise the following:

- *cameraCalib*
- *rectification*
- *logPolarTransform*
- *imageSource*
- *autoAssociativeMemory*
- *myModule (documentation demo)*

These have been committed to the iCub software repository and are documented on the iCub wiki. The principal modules and the cognitive architecture application are described in detail in D2.1. A specification of each of the main modules may be found on the iCub wiki at:
http://eris.liralab.it/wiki/ICub_Cognitive_Architecture
These have been committed to the iCub software repository and are documented on the iCub wiki (http://eris.liralab.it/iCub/dox/html/group__icub__applications.html).

D. Vernon, G. Metta, and G. Sandini, "Embodiment in Cognitive Systems: on the Mutual Dependence of Cognition & Robotics", Invited Chapter to appear in "Embodied Cognitive Systems", J. Gray and S. Nefti-Meziani (Eds.), Institution of Engineering and Technology (IET), UK, 2009

IIT has also continued investigations on machine learning methods suitable for developmental learning, that is, methods which can run efficiently for prolonged periods of time. We investigated along a few directions in the context of the well-known kernel methods:

- Online core vector regression: The common property of all Core Vector algorithms is a reformulation of a Support Vector Machine (SVM) (Cristianini, N. and Shawe-Taylor, J. 2000) optimization problem as a minimum enclosing ball (MEB) problem (Tax, D.M.J. and Duin R.P.W. 1999). This has resulted in three interesting algorithms: Core Vector Machines for Classification (CVC) (Tsang, I.W, Kwok, J.T., Cheung, P-M, 2005) and Regression (CVR) (Tsang, I.W, Kwok, J.T., Lai K.T, 2005), and Ball Vector Classification (BVC) (Tsang, I.W., Kocsor, A., Kwok, J.T. 2007). The latter is a classification algorithm that uses a simpler Enclosing Ball problem, in contrast with the minimum enclosing ball problem used in the two other algorithms. The principal advantage of reducing SVM to an MEB problem is the existence of efficient $(1+\varepsilon)$- approximations that exist for the latter (Badoiu, M. and Clarkson, K.L., 2008). The computational complexity of these approximations is much lower than the complexity to compute an exact solution, as the approximations compute the MEB only for a subset of the data (i.e. the core-set). After considering approaches to transform these algorithms in online versions. We considered two methods for transforming these algorithms into online versions (a streaming variant and the Ball-Vector Classification method). Unfortunately, modifying the BVC algorithm for regression problems is not straightforward. One has to integrate the modifications that were made for CVR in the BVC algorithm, which involves reformulating the SVM optimization problem to a centre-constrained minimum enclosing ball problem. These modifications, however, invalidate the bounds that are used in BVC to obtain the balls' radius a priori. Although I have established bounds for the radius in this new setting, these are too loose for practical use and actually depend on the output values. This is in direct conflict with the context of online learning, as these output values cannot be known in advance. Due to these difficulties, the idea has been abandoned.

- Development of a machine learning interface for YARP. The objective of YARP machine learning interface is to apply this methodology of modularization and abstraction to machine learning algorithms and their applications. The main advantage is that novel implementations of algorithms can easily be deployed on the robot and that applications only depend on an abstract interface, rather than a concrete implementation of an algorithm. Several improvements were made to the framework over the course of this period. An architectural overview of the framework in its current form is shown in Figure 1. One of the most prominent changes is that the transformer, i.e. a component that transforms/pre-processes input samples, has been separated into a distinct module. Consequently, users can initiate multiple transformers to perform sequential pre-processing steps. Another noteworthy change is the integration of prediction functionality in the training module. This eliminates the necessity to run separate training and prediction modules. Nonetheless, it is still possible for any training module to send its model to a (physically) separated prediction module.

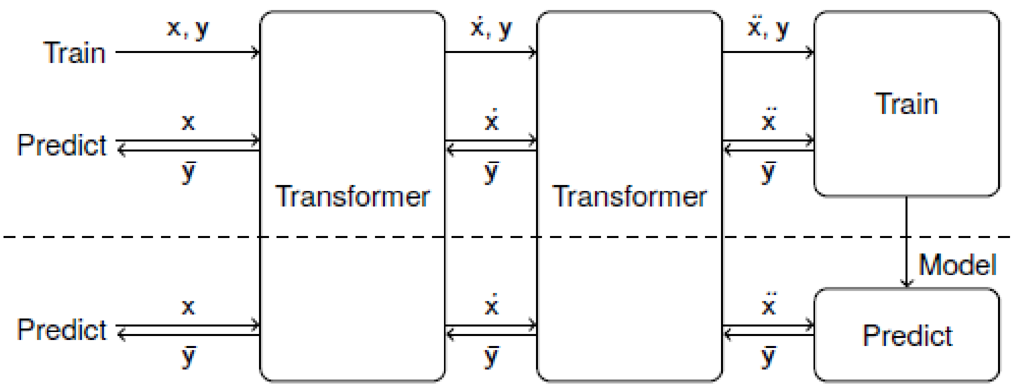


Figure 1: The YARP machine learning architecture.

- Learning the iCub dynamics using LS-SVM. We investigated several techniques for the estimation of forces and torques measured in the kinematic chain of a robot arm. Note that the quantity measured by a force/torque sensor contains the sum of both external and internal forces and torques, i.e. $x=x_I+x_E$, where x_I and x_E refer to the internal and external forces and torques, respectively. The internal forces due to manipulator dynamics (e.g. gravity, inertia) must be compensated in order to accurately detect external forces due to contact with the environment, such that $x_E = x - x_{est}$, with x_{est} being an estimation of the internal forces. In this study, these internal forces were modelled using an analytical model of the relevant physics, an Artificial Neural Network (ANN) and a Least-Squares Support Vector Machine (LS-SVM). This resulted in the book chapter by Fumagalli et al. (2010) – see below.

- Online Kernel Methods with Constant Per-Sample Complexities. The kernel trick is a well-known procedure that has been used to apply a wide variety of linear batch and online learning methods on non-linear problems. It does so by applying the algorithm on input samples *x* that are mapped into a (usually) higher dimensional feature space – $\Phi(x)$. In algorithms that depend solely on inner products between inputs samples, these inner products can thus be substituted by a kernel function $k(xi,xj)=\langle\Phi(x_i),\Phi(x_j)\rangle$. This kernel function is evaluated directly in the original input space, without the necessity to actually compute the mapping $\Phi(\cdot)$. The prediction function is then described as a linear combination of kernel evaluations (i.e. the kernel expansion), such that:

$$f(x) = \langle w, \Phi(x) \rangle = \sum_i \alpha_i k(x_i, x)$$

  Since we only need the inner products between samples, there is no need to describe the weight vector:

$$w = \sum_i \alpha_i \Phi(x_i)$$

  or the input samples explicitly in the feature space. The key property of the kernel trick is thus the implicit operation of an algorithm in a hypothetical feature space, without having to compute this mapping explicitly. However, the expansion causes the time and space complexities of the algorithm to increase linearly with the number of training samples. These linear space and time complexities are in direct conflict with the desideratum of continuous learning in developmental robotics. Any learning method that is supposed to run continuously for the entire operational runtime of a robot must have at most constant time and space complexities. One possible way of avoiding this linear complexity is to limit the growth of the kernel expansion. This can be done either by limiting the expansion to a fixed size or by combining input samples that are linear dependent in the feature space into one. A drastically different approach is to avoid the kernel expansion altogether by explicitly computing the feature mapping and *w* in the feature space. In case of the polynomial kernel this can be done easily, since the dimension of the corresponding feature space is finite. The polynomial kernel function can be decomposed as:

$$k(x_i, x_j) = \left(R + \langle x_i, x_j \rangle^d\right) = \sum_{s=0}^{d} \binom{d}{s} R^{d-s} \langle x_i, x_j \rangle^s$$

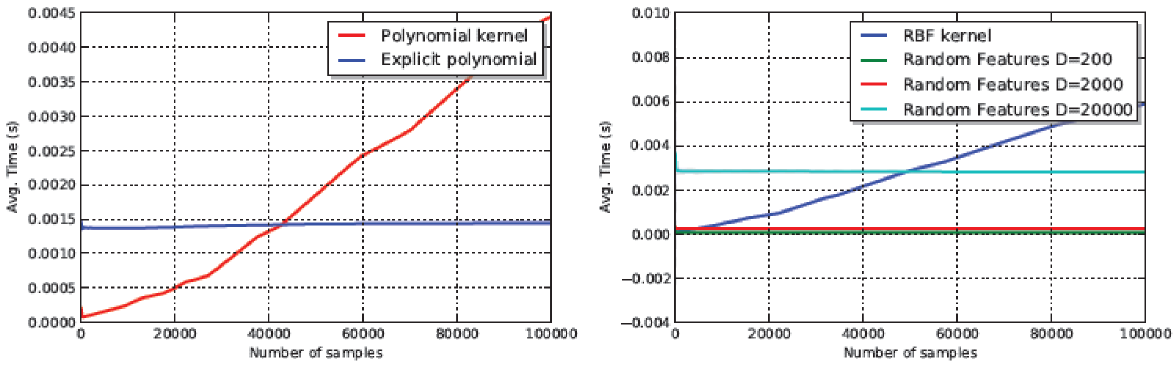
  where *d* is the degree and *n* is the input dimensionality. Note that explicit computation of this mapping is computationally unfeasible for large d and n. Figure 6(a) demonstrates the time needed for each training sample using Passive-Aggressive for Regression (PAR) with both implicit and explicit evaluation of the polynomial kernel function. This figure clearly demonstrates the linear complexity of implicit kernel evaluation due to the kernel expansion and the constant complexity when using explicit kernel evaluation. The feature space of the RBF kernel is infinitely dimensional and the feature mapping can therefore not be computed explicitly. Rahimi and Recht, however, propose a method to approximate shift invariant kernels using Fourier transforms. They derive stochastic mappings $z_\omega(x)$ (i.e. a random feature), such that the inner product of this mapping is an unbiased estimate of the RBF kernel, i.e.

$$k(x_i, x_j) = \exp\left(-\gamma \|x_i - x_j\|^2\right) = E\left[\langle z_\omega(x_i), z_\omega(x_j) \rangle\right]$$

Since $z_\omega(x)$ is stochastic, we can lower the variance of the approximation by concatenating D random mappings and normalizing each component for D. A comparison between the implicit RBF kernel and random feature approximation with different settings for D is shown in Figure 2. Additionally, Figure 3 shows the approximation accuracy of the random feature kernel. These figures demonstrate that the number of projections D effectively controls the trade off between speed and accuracy. A novel direction for explicit feature mappings can be the composition of more complex feature spaces by concatenating various explicit mappings. Contrary to traditional kernels that have to satisfy Mercer's conditions, there are no strict requirements for explicit feature mappings. A particularly interesting approach would be to construct "hybrid" kernels by combining explicit polynomials or random features with handcrafted, domain specific features.

We considered an online implementation of LS-SVM with random features kernel using incremental least square (with regularization). The Regularized Least Square (LS-SVM) works well also for non IID data and therefore is particularly indicated for robotic online learning (see Figure 4). These models (learnt) are meant to replace the handcrafted models for reaching and dynamics (force control).

Fumagalli M., Gijsberts, A., Ivaldi, S., Jamone, L., Metta, G., Natale, L., Nori, F., Sandini, G. Learning to Exploit Proximal Force Sensing: a Comparison Approach. From Motor Learning to Interaction Learning in Robots, Elsevier. (2010).



(a) Polynomial (b) RBF

Figure 2: Comparison of average time per training sample with Passive-Aggressive for Regression when using implicit and explicit evaluation of the polynomial and RBF kernels. The explicit RBF kernel is approximated using random features with varying dimensions.

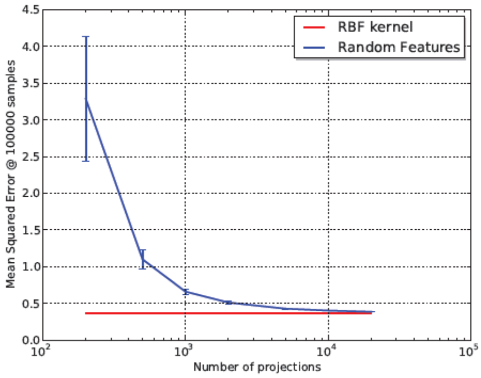


Figure 3: Approximation accuracy of random feature pre-processing with respect to the number of dimensions D. The horizontal bars indicate the standard deviations as obtained with 50 random trials.

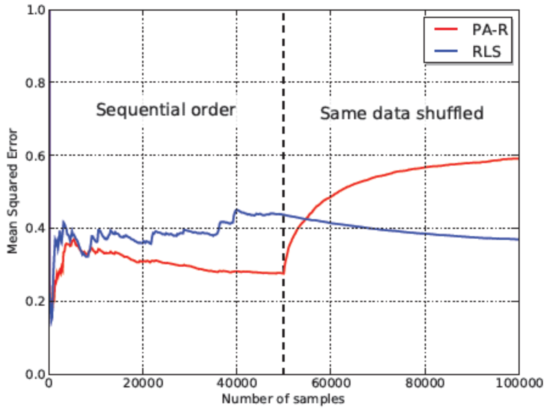


Figure 4: Comparison of Passive Aggressive Regression (PAR) and incremental Regularized Least Square (RLS) with random feature pre-processing. After initially training on 50000 samples in sequential order, both algorithms are fed the same samples in randomized order. Contrary to PAR, RLS constructs a model that generalizes well on the data and is thus unaffected by this abrupt change in ordering.

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Ivor W. Tsang, James T. Kwok, and Pak-Ming Cheung. Core vector machines: Fast SVM training on very large data sets. Journal for Machine Learning Research, 6:363–392, 2005.

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Ivor W. Tsang, Andras Kocsor, and James T. Kwok. Simpler core vector machines with enclosing balls. In ICML ’07: Proceedings of the 24th international conference on Machine learning, pages 911–918, New York, NY, USA, 2007. ACM.

Mihai Badoiu and Kenneth L. Clarkson. Optimal core-sets for balls. Computational Geometry: Theory and Applications, 40(1):14–22, 2008.

UNIZH

Certain aspects of the approach to cognition which are described in the Deliverable 2.1 can be also found in the following paper:

Pfeifer, R., Lungarella, M. and Iida, F. (2007b). Self-organization, embodiment, and biologically inspired robotics. Science, 318: 1088-1093.

UNIUP

As mentioned earlier, UNIUP activity in WP2 concentrated on the formulation of a set of scenarios to guide the implementation of the Cognitive Roadmap in the iCub. In particular, material was added the sections on Core Abilities: in particular to the sections on Objects, and People. Material was added to the sections on Development of Posture and Locomotion and Development of Reaching and Manipulation (four new subsections on Reaching, Grasping, Bimanual Coordination, and Manipulation). Material was added to the Development of Social Abilities. Deviations from the planned work (problems, solutions, etc.).

von Hofsten,C. (2009) Action, the foundation for cognitive development. Scandinavian Journal of Psychology, 51, 1-7.

UNIHER

Cognitive development of prospective and episodic memory based action selection in social gesture communication and turn-taking interactions with humans was integrated and enhanced by short-term memory and gaze detection capabilities for improved ontogenetic mechanisms for Task 2.6 Software implementation of the iCub cognitive architecture. Due to its enabling role for gesture communication, the bulk of this work is reported under WP5N (including scientific work on the Interaction History Architecture (IHA), software release and demo).

IST

The work in this Workpackage has focused on the consolidation of the approaches to cognitive development presented during the previous years of the project. The approach considers the development stages roughly organized as:

1. Learning about the self (sensory-motor coordination);

2. Selective Attention (information selection);
3. Learning about objects (affordances);
4. Learning about others (imitation).

The work on sensorimotor coordination focused on “smart” exploration strategies for the generation of bodily motions in order to maximize the improvement in sensorimotor mapping. Instead of using random movements, active learning techniques have been studied and implemented to allow the robot to determine on-line the next exploratory movement, thus improving the efficiency of learning.

The work on eye-neck coordination has continued in collaboration with the University of Uppsala and controllers were learned from existing data recordings from humans (infants). Experiments were performed on the iCub, in collaboration with Scuola Superiore Sant’Anna on the predictive abilities in tracking objects across occlusions.

The work on the attention system has focused on optimizing the operation of the iCub’s multimodal attention system and on the study of foveal sensor morphologies to reduce the visual information to process at each time step. Foveation plays a fundamental role on natural systems with gaze shifting capabilities, since it allows to speed up computations (and thus improve reaction times) at the cost of resolution in the peripheral view field. Studies were directed to the mathematical basis of foveation and to the development of a sensor morphology adapted to the organism’s sensory experience.

Work on object affordances concentrated on developing the software modules to support both the learning and the exploitation of learned affordances. Such modules will not only constitute the basis for final demonstrations but also future work on using affordances to predict, recognize and plan actions.
Additional work was developed in the grasping affordances. We studied how an agent can learn from exploration what are the best grasping points in general objects and how grasping sequences can be optimized for each particular object.

In the fifth year of the project, IST has developed the following main activities:

3D model-based tracking – Robust tracking of object is essential for the development of multiple sensorimotor coordination tasks. Following the work of previous years we have continued research on this topic and implemented in the iCub software architecture a tracking method that is robust to occlusions and motion blur, typical of robotics applications. The method has been used in several demonstrations of the iCub and to provide a basic perception mechanism for developing advances sensorimotor coordination tasks, such as predictive tracking across occlusions, a joint work with Scuola Superiore Sant’Anna.

Predictive Tracking across Occlusions on the iCub robot. E. Falotico, M. Taiana, D. Zambrano, A. Bernardino, J. Santos-Victor, C. Laschi, P. Dario. 9th IEEE-RAS International Conference on Humanoid Robots, Paris, December 2009.

Tracking objects with generic calibrated sensors: an algorithm based on color and 3D shape features, M. Taiana, J. Santos, J. Gaspar, J. Nascimento, A. Bernardino, P. Lima, Robotics and Autonomous Systems, in press, 2009.

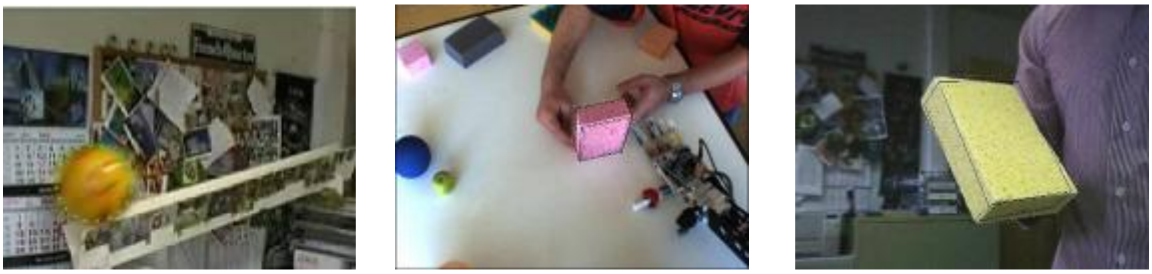
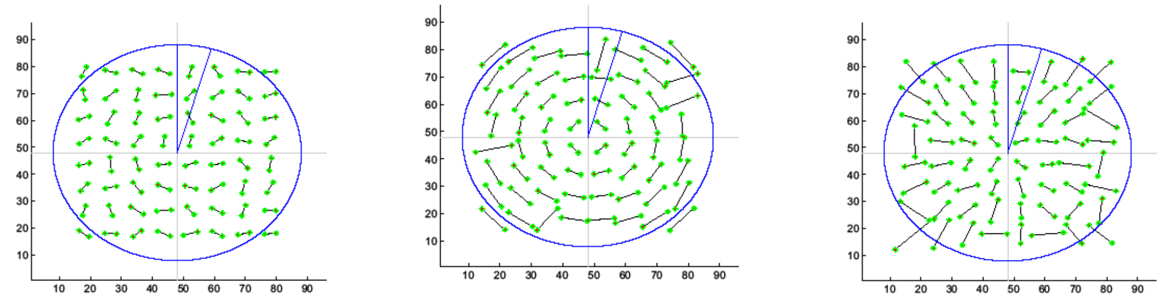


Figure 5: Examples of robust model based tracking in cluttered background with particle filters.

Space variant sensing – The space variant structure of the retina and of the retino-cortical mapping has major implications on the nature of visual processing in humans and in cognition in general. IST has conducted research on space variant sensing in two aspects: (a) the analysis of the mapping and on the generation of efficient computational constructs and (b) the optimal layout of the resolution over space according to the distribution of observed velocities, in an ecological perspective.



(a) (b) (c)

Figure 6: Self-organization of the retinal morphology given motion stimuli. (a) detectors initialized with random orientation. (b), (c) The final receptor-pairs configurations after observing rotating or scaled input pattern for time steps.

Smooth Foveal Vision with Gaussian Receptive Fields. D. Pamplona, A. Bernardino. 9th IEEE-RAS International Conference on Humanoid Robots, Paris, December 2009.

Evolving Predictive Visual Motion Detectors. J. Ruesch, A. Bernardino. IEEE - International Conference on Decision and Learning, Shanghai, China, 2009.

Memory-space representations – As an extension of the work previously developed in the attention architecture of the iCub, IST has investigated the use of representations for objects that can be stored in a long-term memory of the system for posterior recognition of previously seen objects.

From Pixels to Objects: Enabling a spatial model for humanoid social robots, Dario Figueira, Manuel Lopes, Rodrigo Ventura, Jonas Ruesch, Proc. of ICRA 2009 - IEEE International Conference on Robotics and Automation (ICRA-09), Kobe, Japan, 2009

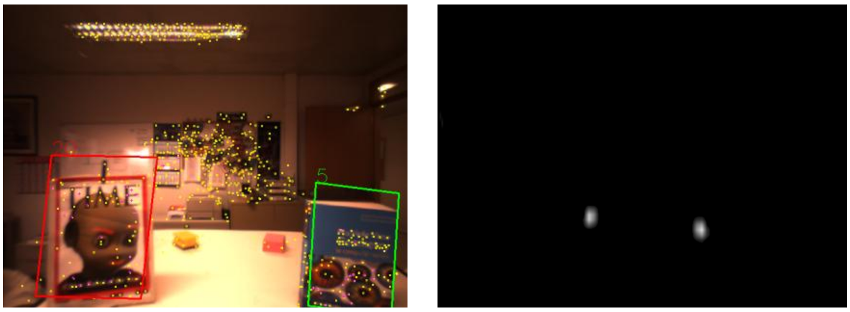


Figure 7: Example of object recognition (left) and conspicuity map (right).

Deviations from the project work-programme

None.

List of deliverables

Del. No.	Deliverable name	Workpackage no.	Date due	Actual/Forecast delivery date	Lead contractor
D2.1	A Roadmap for the Development of Cognitive Capabilities in Humanoid Robots	2	M65	M65	UGDIST
D2.2	Software Implementation of the iCub Cognitive Architecture (version 2.0).	2	M65	M65	UGDIST

List of milestones

Milestone. No.	Milestone name	Workpackage no.	Date due
M4.3	Release of version 2.0 of the iCub software	2	M65

WP3 – Sensorimotor Coordination

Workpackage objectives

In this Workpackage, we studied and modelled the development of sensorimotor coordination and sensorimotor mapping. We identify how the sensorimotor system is determined by biology, how this is expressed in development, and how experience enters into the process in forming reliable and sophisticated tools for exploring and manipulating the outside world. Sensory information (visual, proprioceptive, auditory) necessary to organize goal-directed actions is considered. These aspects are investigated in humans and transferred into the cognitive architecture of the artificial system. There are two main objectives of WP3:

1. Model how sensorimotor systems evolve from sets of relatively independent mechanisms to unified functional systems. In particular, we study and model the ontogenesis of looking and reaching for example by asking the following questions: How does gaze control evolve from the saccadic behaviour of newborns to the precise and dynamic mode of control that takes into account both the movement of the actor and the motion of objects in the surrounding? How does reaching evolve from the crude coordination in newborns to the sophisticated and skilful manipulation in older children? In addition, we model how different sensorimotor maps (for gaze/head orienting, for reaching, for grasping, etc.) can be fused to form a subjectively unitary perception/action system. We look also at how the brain coordinates different effectors to form a "pragmatic" representation of the external world using neurophysiological, psychophysical, and robotics techniques. More specifically, the experiments considered are derived from Section 17 ("empirical investigations") of Deliverable 2.1.
2. Investigate and model the role of motor representation as tools serving not only action but also perception. This topic, partially covered by WP4, WP5N, clearly benefits from a unifying vision based on the idea that the motor system (at least at its representational level) forms the "active filter" carving out passively perceived stimuli by means of attentional or "active perception" processes.

As a result of WP2 the "innate" abilities were defined and the focus of the effort in months 49-65 was in the implementation of these phylogenetic abilities specifically for the iCub. No new tasks have been added in the period month 49 to month 65. Existing tasks addressed the implementation and integration of sensorimotor skills in the Cognitive Architecture. The neuroscience partners of the project coordinated contributions to the activities of this WP.

Locomotion, although originally viewed as a simple task in autonomous relocation of the iCub, in now understood to be a complex and essential part of the complete sensorimotor capability of the iCub and was addressed explicitly in this Workpackage rather than in WP7 as it was in the first year of the project.

This WP contributed mostly to objectives SO2 and SO3 described above.

Active tasks

Task 3.1: Modelling the ontogenesis of gaze control and eye-head coordination, for example to study and model oculomotor involvement in orienting of visuospatial attention and visuomotor priming in object-directed actions.

Task 3.2: Modelling the ontogenesis of functional reaching and grasping of arm-hand cooperation (Grasping - haptic) to study aspects such as how to predict reaching/grasping outcomes and how to code action goals.

Task 3.3: Bimanual Coordination. Activity here will be devoted to a relatively unexplored area (at least with respect to the scientific literature on manual reaching and grasping) of how bimanual coordination develops.

Task 3.5: Neuroscience and robotic experiments on the functional development of cortical representations (i.e. sensorimotor synergies and somatotopy).

Task 3.6: Modelling of locomotion and transitions between locomotion and rest (sitting) states; including simulation and robotic experiments on the autonomous exercise of locomotive behaviour.

Task 3.7: Superposition of rhythmic and discrete movements.

Task 3.9: Software implementation of the phylogenetic abilities specifically for the iCub & integration in the iCub Cognitive Architecture.

Task 3.10: Electrophysiological study of human sensorimotor representations.

Progress towards objectives

The brain collects information about the environment through sensory systems and computes motor responses. How sensory and motor systems interact and how higher cognitive processes contribute to these computations is not fully understood. The dominant theory views input systems as modular, filtering sensory input in a feedforward manner to yield perceptual processes[1,2], which, after possible interaction with attention, emotion, and memory modules, impact on motor systems controlling actions[3]. Accordingly, the posterior part of the cortex of higher mammals is mainly concerned with sensory information, whereas the frontal motor system serves a slave role under the dictate of perceptual and cognitive systems.

Recent years have seen major challenges to this established view. The discovery of sensorimotor neurons in macaque monkeys prompted a new perspective[4]. Visuomotor neurons, discharging during both goal-directed actions and visual stimulation, were first discovered in the frontal eye field (FEF)[5], where 40% of the cells are bimodal in this sense. Ventral premotor recordings further confirmed that sensorimotor neurons are the rule rather than the exception. Macaque area F4 shows trimodal neurons responding during movements, tactile stimulation of concordant body parts, and visual input from concordant regions of peripersonal space. These neurons seem to code the space around us in 'motor coordinates', therefore providing a direct link between a stimulus and the most appropriate movement to reach it[6]. Monkey premotor area F5 houses (i) *canonical visuomotor neurons* active during goal-directed action execution (e.g. grasping) and the visual perception of the *object* of the action, and (ii) *mirror neurons* (MNs), which activate during action execution and during the observation of another individual (monkey or human) performing a similar *action*[7-9]. Transcranial magnetic stimulation (TMS) of motor cortex[10] and neuroimaging studies during action observation[11] have shown that a similar observation/execution matching mechanism exists in humans as well. MNs can be multimodal, also responding to the sounds of actions (e.g., peanut breaking)[12-15]. The multimodal action-specificity of MNs indicates that sensory, cognitive, and motor processes are functionally interwoven and that motor circuits play a role in action perception and in connecting basic actions to the goals they address, suggesting a mechanism for an important distinction in the theory of action[16,17]. Accordingly, perception, cognition and motor control share neuronal mechanisms and MNs, along with other sensorimotor neurons, are key to these shared functions[11,18,19]. In working memory tasks, cells with similar stimulus-specificity but located in both frontal and temporal areas could be shown to be mutually dependent functionally, therefore providing strong evidence for distributed action-perception circuits in memory processing[20].

The postulate that action and perception are interwoven with each other and form the basis of higher cognition is in contrast with the established modular view according to which perceptually-related activity in motor systems could still be accounted for in the sense of bottom-up effects. As the importance of sensory input on the control of actions is widely agreed upon, an evaluation of, and, eventually, decision between, the two alternative positions critically depends on the question whether activity in motor systems *is relevant for* perception and comprehension[21].

In summary, along these lines we realized a layered controller system for the iCub including:

- **Spinal behaviours:** e.g. rhythmic movement and basic synergies, force feedback. We developed an architecture for the generation of discrete and rhythmic movements where trajectories can be modulated by high-level commands and sensory feedback. See EPFL and UGDIST/IIT sections below. USFD (only lately) has investigated aspects in connection with whole-body motion (task 3.6 and 3.7).
- **Eye movements and attention:** an attention system was developed which includes sensory input processing (vision and audition), eye-neck coordination, eye movements (smooth pursuit, saccades, VOR and vergence). Methods for tracking behind occlusions have been also investigated. See work by SSSA, UNIZH, and IST (task 3.1).
- **Reaching and body schemas:** a robust task-space reaching controller has been developed and methods for learning internal models tested. Specifically, generic inverse kinematics models and human-like trajectory generation has been implemented for the iCub by taking into account various constraints such as joint limits, obstacles, redundancy and singularities. Examples can be found in the work of UGDIST/IIT, EPFL, IST, and SSSA (task 3.2).
- **Grasping:** finally, based on reaching and orienting behaviours, a grasping module has been implemented. This allows the coordination of looking (for a potential target), reaching for it (placing the hand close to the target) and attempting a grasping motion (or another basic action). This work is described in the sub-sections of UGDIST/IIT and IST (task 3.2).

Extensive investigation on the development of these abilities and their final form in adult humans has been carried out. Examples are reported below both in the work of UNIFE and UNIUP (task 3.3, 3.5 and 3.10) but also with joint experiments (and publications), e.g. with IST, SSSA. Deliverable D3.1 and the more recent D3.7 testify this prolific activity (also in terms of publications). These results have formed our guides to the implementation of robotic models (task 3.9) although they details are not always fully "neural" based. We acknowledge instead the difference between the hardware of the brain and our digital computers and tried to mimic only certain properties of the solutions employed by the brain. One example is in serial vs. parallel implementation of computers vs. the brain. Where we use optimization methods, the brain might be employing global states of equilibrium to find the same solution. It is to be expected that artificial cognition on digital computers is not going to simulate the fine details of the brain (though running simulations is entirely possible, making them work in real-time on a humanoid robot poses a set of additional challenges).

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Zero force control

The goal of this work is to allow compliant control by employing the iCub force/torque sensors placed in the arms and legs.

In general, the dynamics of a robotic manipulator can be described by the following equation:

$$M(q)\ddot{q} + C(q,\dot{q}) + G(q) = u - J^T F$$

Where $q, \dot{q}, \ddot{q}$ represent the joint angle, velocities and accelerations, $M(q), C(q,\dot{q}), G(q)$ are the inertia matrix and the vector of centrifugal, Coriolis and gravitational joint torques. The effect of the external forces applied at the end-effector of the manipulator is projected in the joint space by the manipulator's geometric Jacobian. In order to purely react to measured forces, the command variable u should be chosen as:

$$u = J^T F$$

The force sensors are mounted in the upper part of each limb (root of the kinematic chain) of the iCub robot. Therefore, forces and torques need to be referred to the end point.

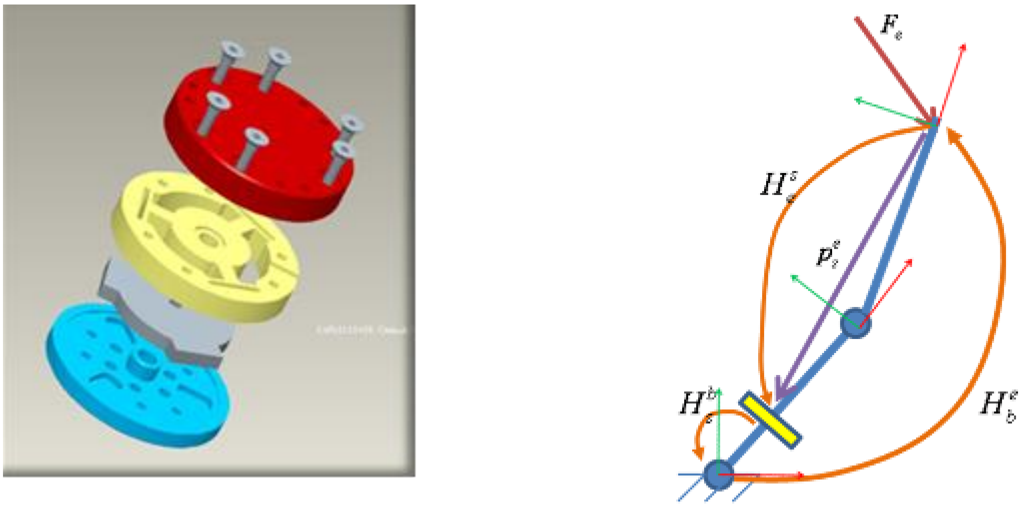

Figure 8: Left panel, the force-torque sensor mechanics (also in WP7): the yellow part in the middle is sensorized by employing semiconductor stain gauges. Right panel, reference frames for the robot sensor kinematics as described in text.

Measured forces can thus be transformed as follows:

$$F = H_s^b(q) F_s$$

where F_s are the forces and torques measured by the sensors and $H_s^b(q)$ is the 6x6 matrix, providing for the transformation of the measured forces into their equivalent at the end-effector, in the base frame (here we consider that the forces measured by the force-torque sensor are only the external force, thus avoiding to consider the inner dynamic of the arm).

$$H_s^b = H_s^e H_e^b$$

where:

$$H_s^e = \begin{bmatrix} R_s^e & 0 \\ R_s^e \hat{p}_s^e & R_s^e \end{bmatrix} \text{ and } H_e^b = \begin{bmatrix} R_e^b & 0 \\ 0 & R_e^b \end{bmatrix}$$

The control law is therefore:

$$u = KJ^T(q)H(q,d)_s^b F_s$$

Being K a *nxn* gain matrix.

More in general, desired forces F_d can be imposed for interaction purposes. The control strategy can thus be generalized as:

$$u = KJ^T(q)H(q,d)_s^b (F_s - F_d)$$

which allows (in general) imposing a given mechanical impedance to the robot arm (there are considerations about redundancy and the number of available measurements that are not discussed further here for brevity).

Reaching: the Cartesian Controller Interface

Given the Cartesian position of an object to be grasped as result of a visual recognition process, the complexity of the reaching task is tackled with a modular approach (Figure 9): 1) in the first stage the arm joints configuration which achieves the complete desired pose (i.e. end-effector position and orientation) is determined through a nonlinear optimizer taking into account all the imposed constraints; 2) human-like quasi-straight trajectories are then generated independently by a biologically inspired controller.

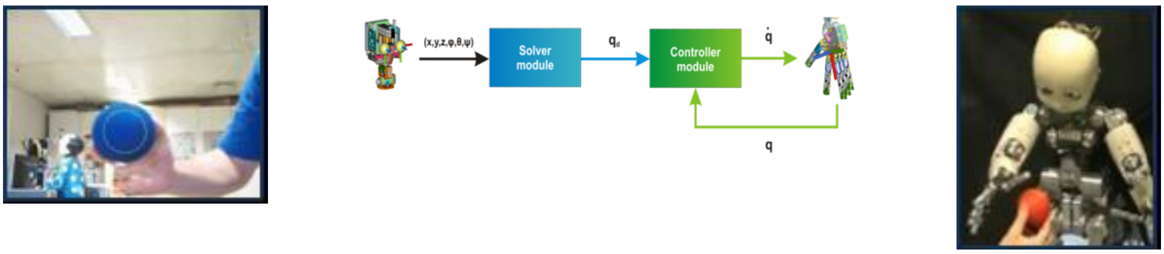

Figure 9: Diagram of implemented Cartesian controller.

Solver module

To sidestep the weaknesses of kinematic inversion methods that do not account automatically for joints constraints (they usually resort to the null-space projection which has to be accurately tuned), a solution based upon a constrained optimization method has been adopted for the solver module. In particular, we used IpOpt which is a public domain software package designed for large-scale nonlinear optimization problems and is applied here to find solutions for the inverse problem as follows:

$$\mathbf{q} = \arg \min_{\mathbf{q} \in R^{10}} \left(\left\| \boldsymbol{\alpha}_{\mathbf{d}} - K_{\alpha}(\mathbf{q}) \right\|^2 + w \cdot \left\| \mathbf{q}_{rest} - \mathbf{q} \right\|^2 \right) \quad \text{s.t.} \begin{cases} 0 < \left\| \mathbf{x}_{\mathbf{d}} - K_x(\mathbf{q}) \right\|^2 < \varepsilon \\ \mathbf{q}_{\mathrm{L}} < \mathbf{q} < \mathbf{q}_{\mathrm{U}} \end{cases}$$

where the solution **q** is the joints vector with 10 components (7 joints for arm, 3 joints for torso or any other number of joints depending on the task) that is guaranteed to be found within the physical bounds expressed by $\mathbf{q}_L$ and $\mathbf{q}_U$; $\mathbf{x}_\mathbf{d} \equiv (x,y,z)_d$ is the positional part of the desired pose, $\boldsymbol{\alpha}_\mathbf{d}$ is the desired orientation and K_x and K_α are the forward kinematic maps for the position and orientation part, respectively; $\mathbf{q}_{\mathbf{rest}}$ is used to keep torso as close as possible (weighting with a positive factor $w<1$) to the vertical position while reaching and ε is a small number in the range of $10^{-4} \div 10^{-5}$.

It shall be pointed out how this formulation of the problem allows prioritizing reaching of the target position, which plays a primary role, with respect to reaching of the desired orientation by splitting the two tasks and treating the former as a further nonlinear constraint, hence evaluated before any computation in the orientation space, and the latter as the actual function to be minimized.

A non secondary benefit provided by IpOpt is the possibility to easily describe any additional constraints both in joint and task space as for example the set of linear inequalities required in managing the tendon limits of the iCub shoulder. These cover the convex hull of the shoulder movements.

Controller module

The generation of velocity profile is achieved by applying the concept of Multi-Referential Systems where two minimum-jerk generators, one in joint space and one in task space (Figure 10), produce velocity commands simultaneously; a coherence constraint is enforced by using a Lagrangian multipliers approach which also modulates the relative influence of joint vs. task space trajectory. For example, joint angle limits can be avoided while maintaining a straight trajectory. The advantage of such a redundant representation of the movement is that a quasi-straight line trajectory profile can be generated for the end-effector in the task space reproducing a human-like behaviour, while retaining converge property and robustness against singularities (the method is similar to the damped least square algorithm).

The algorithm has two steps:

Step 1. At any time each trajectory generator takes the desired target found by the optimization process and outputs the corresponding velocity profile which achieves the target following a minimum-jerk trajectory. Translating in formulas we have:

$$\dot{q}_d = f\left(a_{q,i},T,\tau\right);\quad \dot{x}_d = f\left(a_{x,i},T,\tau\right);\quad \text{with } f\left(a_{\circ,i},T,\tau\right)=\sum_{i=1}^{5}\frac{i\cdot a_{\circ,i}}{T}\tau^{i-1}$$

where *T* is the execution time, ***T*** is the normalized time (in [0, 1]) and $a_{a,i}$ represents a set of coefficients which depend on the initial velocity, the duration *T* and the difference between the target and the current position.

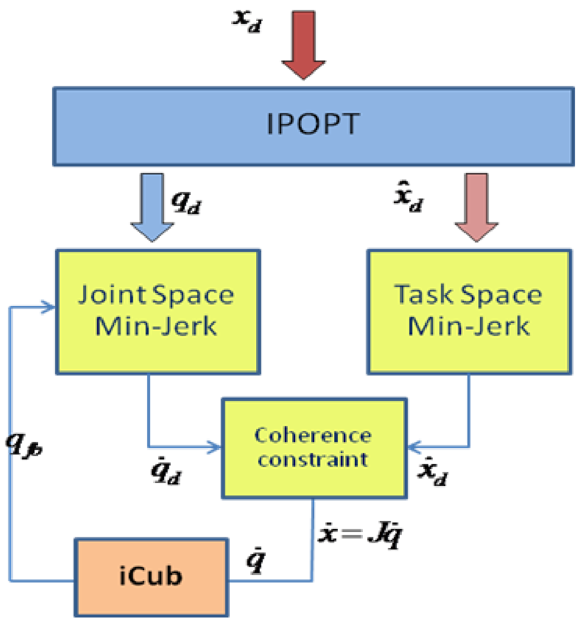

Figure 10: The Multi-Referential controllers scheme described in the paper by Hersch et al.

Step 2. Since the temporary desired velocities do not verify the kinematic constraint given by, being *J* the Jacobian of the kinematic map, as the two systems evolve independently, the coherence is enforced by applying a Lagrangian multipliers method which identifies the joints velocities by solving the minimization problem:

$$\min_{\dot{q}_t,\dot{x}_t} \frac{1}{2}\left(\left(\dot{q}_t-\dot{q}_t^d\right)^T W_q\left(\dot{q}_t-\dot{q}_t^d\right)+\left(\dot{x}_t-\dot{x}_t^d\right)^T W_x\left(\dot{x}_t-\dot{x}_t^d\right)\right)\quad s.t.\quad \dot{x}_t = J\dot{q}_t$$

whose solution is:

$$\dot{q}_{t+1} = \dot{q}_t^d + W_q^{-1}J^T\left(W_x^{-1}+JW_q^{-1}J^T\right)^{-1}\left(\dot{x}_t^d - J\dot{q}_t^d\right)$$

with W_q and W_x appropriate semi-definite diagonal matrices.

With respect to the original implementation of the algorithm (see Hersch et al.), VITE's controllers have been replaced with time-based minimum-jerk generators that provide much better performance in terms of level of similarity between the resulting velocity profiles and the desired human-like prototypes especially for short trajectories (see Figure 11).

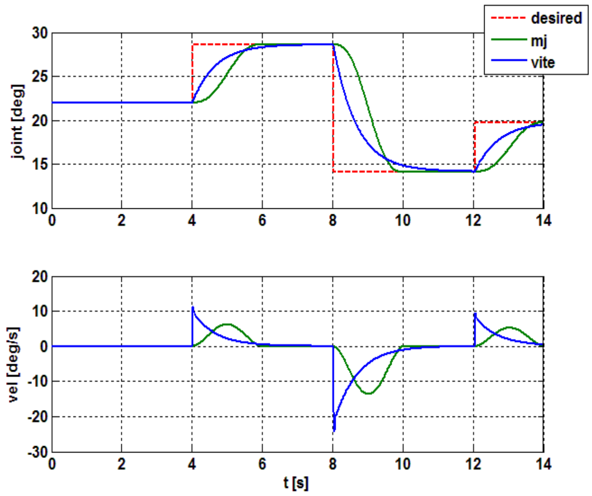

Figure 11: Comparison between VITE and Min-Jerk Generator.

One crucial aspect of the "new" generators is that they act in open loop for the execution time *T*; soon afterwards the new position (i.e. the new joints configuration just attained) is read back yielding a further error (much smaller this time) which in turn forces the system to react, thus playing the role of a closed loop component sampled at the end of each trajectory. The error is however small and it is determined by how good the velocities commands are executed by the low level PID's running on the embedded iCub controllers.

Cartesian Interface

From the software standpoint a special YARP interface has been devised in order to provide an abstraction level embedded into the software for inverting/controlling the kinematic of the iCub. The purpose is twofold: 1) to allow the controller to run directly aboard the robot (i.e. on the PC104 hub) getting around the speed limitation due to the network by accessing the resources internal to the robot; 2) to specify a set of interface methods (such as go_to_pose(), get_pose(), set_trajectory_time(), …) that enable the user to configure and control the robot limb according to the needs without the use of an independent *ad hoc* YARP module.

Concerning the first issue, a considerable gain in controller reactivity can be obtained by a factor of about 50% with respect to a standard YARP module running outside the iCub.

The interface resorts to a client/server architecture (Figure 12), where the client consists of a set of user functions, while the server, running locally to the robot, implements the core of the controller based on the Multi-Referential approach as described above. The hidden part is represented by the IpOpt solver which is made available by a more powerful machine of the iCub cluster in order not to overload the internal PC104 CPU.

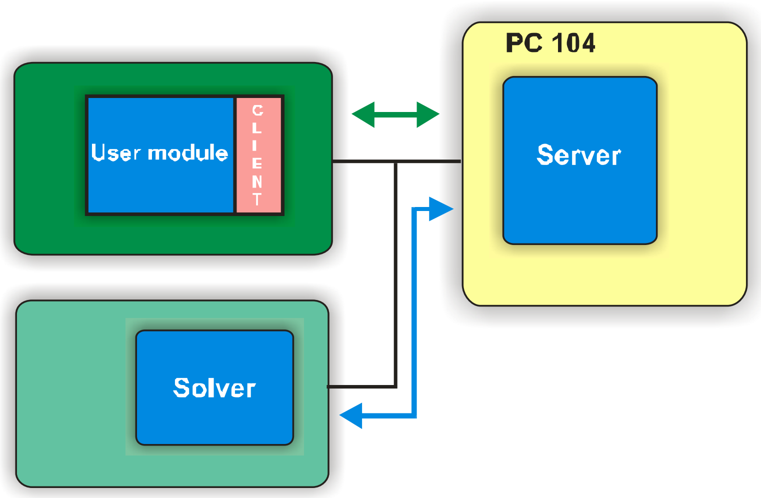

Figure 12: The modular Cartesian Interface architecture.

Grasping: the Action Primitives Library

By relying on the YARP Cartesian Interface, a library has been developed with aim of providing the user a collection of action primitives such as reach(), grasp(), tap(), … along with an easy way to combine them together forming higher level actions in order to eventually execute more sophisticated tasks without reference to the motion control details.

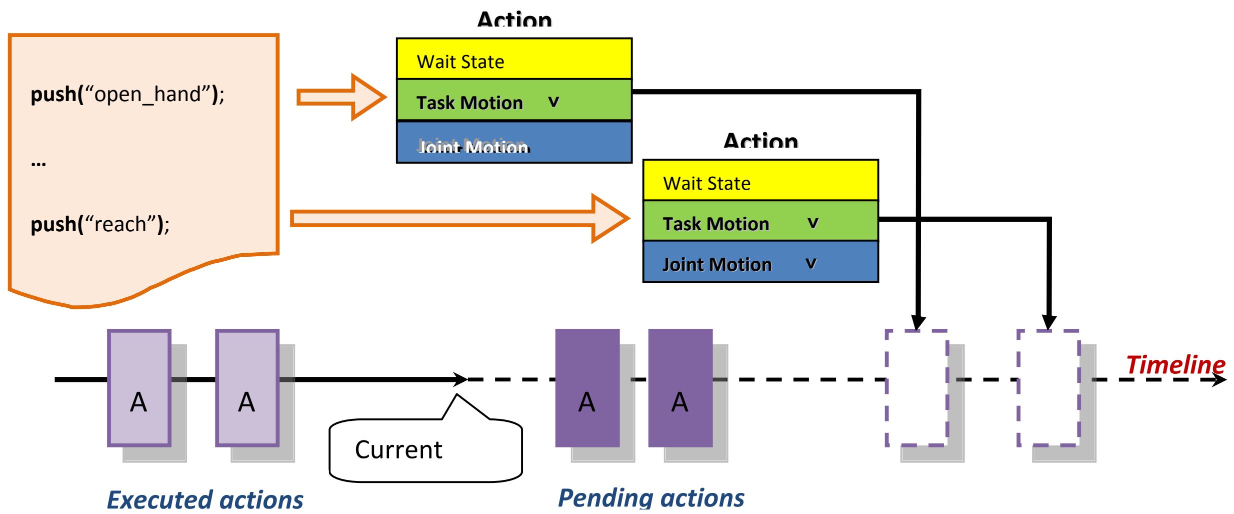

Figure 13: The Actions Queue.

Central to the library's implementation is the concept of action. An action is a "request" for an execution of three different tasks according to its internal selector: 1) it can ask the system to wait for a specified time interval; 2) it can ask to steer the arm to a specified pose, hence performing a movement in task space; 3) it can command the execution of some predefined sequences in joint space identified by a tag; besides there exists the possibility of generating one action a task of type 2) simultaneously to a task of type 3). Moreover, whenever an action is produced from within the code the corresponding request item is pushed at the bottom of actions queue. Therefore, the user can identify suitable fingers movements in the joint space, associate proper grasping 3D points together with hand posture and finally execute the grasping task as a harmonious combination of a reaching movement and fingers actuations, complying with the time requirements of the synchronized sequence.

To detect a finger contact either with the graspable object or with another finger in order to stop the motion preventing any damage, readouts from the low-level control status are profitably exploited, measuring whether the voltage error overcomes a specified threshold. Recently, in this respect, a more robust model-based approach has been conceived which measures the discrepancy between the current finger motion and the one foreseen as result of first order approximation of the multi-springs system. Workpackage 4 contains more details on the development of grasping, exploration of objects and affordances (therefore naturally connecting to the results of Workpackage 3).

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Bimanual coordination

RobotCub supported porting of the architecture from the Gnosys project through collaboration at IIT with Pietro Morasso and Vishu Mohan. This resulted in a paper (and videos) available from the RobotCub paper download page (http://www.robotcub.org/misc/review5/papers/papers.html):

Mohan, V., Morasso, P., Metta, G., Sandini, G. A biomimetic, force-field based computational model for motion planning and bimanual coordination in humanoid robots. Autonomous Robots. (in press). pp.1-46 (2009).

SSSA

Sensorimotor maps for reaching and grasping – The sensorimotor maps were created in a motor babbling phase in which information of the joints of the manipulator and visual features of the end-effector were collected. A forward model of the robot was constructed with the babbling information previously stored using the ANFIS neural networks. The forward model constructed was used to initialize an image Jacobian. The image Jacobian serves in a reaching task using a visual servo controller. The controller and vision modules were tested in the iCub simulator and in the iCub robot. The modules have been uploaded in the repository. For further information refer to the deliverable D3.5 month 42, and to the publication:

Daniel Fernando Tello Gamarra, Kenneth Pinpin, Cecilia Laschi, Paolo Dario. “Forward Model Applied in Visual Servoing for a Reaching Task in the iCub Humanoid Robot”, Applied Bionics and Biomechanics Journal, Vol. 6, Issue 3, pp. 345-354, Taylor&Francis 2009.

Smooth pursuit and occlusions – The purpose of smooth pursuit eye movements is to minimize the retinal slip, i.e. the target velocity projected onto the retina, stabilizing the image of the moving object on the fovea. This cannot be achieved by a simple visual negative feedback controller due to the long delays (around 100 ms in the human brain), most of which are caused by visual information processing. During maintained smooth pursuit, the lag in eye movement can be reduced or even cancelled if the target trajectory can be predicted (Fukushima et al. 2002; Wells and Barnes, 1998; Whittaker and Eaholtz, 1982). An important biologically plausible smooth pursuit controller has been proposed by Shibata and Schaal (Shibata et al. 2005). This controller learns to predict the visual target velocity in head coordinates, based on fast on-line statistical learning of the target dynamics. The model proposed by Shibata results as the best solution to represent predictive behaviour and on-line learning in the smooth pursuit eye movement. We proposed a memory-based internal model that stores the model parameters related to the target dynamics added to the Shibata's model (Shibata et al. 2005). Therefore, after a learning phase, the system can recall already experienced target dynamical parameters and improve its performance, e.g. in terms of convergence speed. This model has been implemented and tested both on the iCub simulator and on the iCub platform. The software code has been duly stored in the repository.

The proposed model can represent the target dynamics even if the target is occluded. This work, in collaboration with IST, solves the problem of tracking targets across occlusions with predictive behaviour, like in humans. Tracking is based on an integration model of smooth pursuit and saccades. Smooth pursuit is able to predict velocity of target dynamics. When the target is occluded smooth pursuit is stopped, the internal model predicts the reappearance of the target and the gaze arrives at the opposite side of the occluder when the target reappears, then the smooth pursuit restarts. The model has been tested on MATLAB Simulink for sinusoidal dynamics with central occlusion and it has been implemented on iCub robot with the same settings and using a methodology based on 3D particle filter to track the target. This methodology is used to detect transitions between the states of full visibility and occlusions and it minimizes the noise during tracking of moving objects. Also in this case the software modules are available in the repository.

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Publications

Daniel Fernando Tello Gamarra, Kenneth Pinpin, Cecilia Laschi, Paolo Dario. “Forward Model Applied in Visual Servoing for a Reaching Task in the iCub Humanoid Robot”, of Applied Bionics and Biomechanics Journal, Vol. 6, Issue 3, pp. 345-354, Taylor&Francis 2009.

Zambrano D., Falotico E., Manfredi L., and C. Laschi. (2009) .“A model of the smooth pursuit eye movement with prediction and learning”. Applied Bionics and Biomechanics. Accepted.

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UNIZH

The iCub humanoid robot offers a large number of sensors and actuators interlinked in a humanoid morphology and is therefore an ideal test-bed for models of visual attention, vergence, reaching and grasping. UNIZH starting point is that the proper development of the above abilities largely relies on prediction. Prediction, in turn, benefits from good information structure in the sensory stream. We describe work aimed at understanding how appropriate behaviours and adequate sensor morphology can increase information structure in the sensory-motor streaming and improve prediction (Martinez et al 2009).

In order to present how the association and causal relations among the variables (actuators and sensors) are going to depend on the morphology and specific behaviours we have adopted five measurements, all of them fundamentally based on Shannon entropy (Shannon 1948, Cover and Thomas1991), namely, entropy, mutual information, integration, and complexity (Lungarella et al., 2005), which measure statistical regularities among random variables without taking into account temporal precedence. Transfer Entropy is used to quantify causal relations (Schreiber 2000). These measurements were selected to compare the results of experiments, because they allow finding nonlinear statistical patterns and understand why a specific behaviour could give better relations among the data. Shannon entropy: measures the average uncertainty, or information. Given a discrete time series *x(t)* that can have *N* different states, it can be calculated using the state probability distribution according to:

$$H(x) = -\sum_{i=1}^{N} P_x(i) \log P_x(i)$$

Where $P_{x(i)}$ is the probability of *x(t)* being in the i^{th} state. When the uncertainty is maximal the entropy is maximal (uniform distribution), while deviations from equiprobability states result in lowered entropy (increased order and decreased uncertainty). Mutual information measures the deviation from statistical dependence between two or more random variables, quantifying the error we make in assuming *x* and *y* as independent variables. The formal definition of mutual information in terms of single and joint state probability distributions is

$$MI(x, y) = -\sum_{i}\sum_{j} P_{xy}(i, j) \log \frac{P_x(i) P_y(j)}{P_{xy}(i, j)}$$

If x and y are two statistically independent random variables, $P_{xy(i,\ j)}=P_{x(i)}P_{y(j)}$ and $MI(x,y)=0$. For this reason any statistical dependence between x and y yields $MI(x,y)>0$. However in general, the mutual information is insufficient to disclose directed interactions (e.g., causal relationships) between x and y, or between y and x. Integration is the multivariate generalization of mutual information (McGill 1954) and captures the total amount of statistical dependency among a set of random variables Xi forming elements of a system $X=\{X_i\}$. Integration (Tononi et. all 1994) is defined as the difference between the individual entropies of the elements and their joint entropy:

$$I(X) = \sum_i H(X_i) - H(X)$$

As for mutual information, if all elements X_i are statistically independent, $I(X)=0$. Any amount of statistical dependence leads to $I(X)>0$. If a system X has positive integration, and also it has locally segregated dependencies we would expect to find statistical dependence among units at specific spatial scales. A system combining local and global structure has high complexity:

$$C(X) = H(X) - \sum_i H(X_i \mid X - X_i)$$

Where $H(X_i \mid X - X_i)$ is the conditional entropy of one element Xi given the complement $X - X_i$ composing the rest of the system. Transfer entropy is the measure used to disclose the directed flow or transfer of information (also referred to as “causal dependency”) between time series (Schreiber 2000). Given two time series X_t and Y_t, transfer entropy essentially quantifies the deviation from the generalized Markov property: $p(x_{t+1} \mid x_t)=p(x_{t+1} \mid x_t, y_t)$, where p denotes the transition probability. If this deviation is small, then Y does not have relevance on the transition probabilities of system X. Otherwise, if the deviation is large, then the assumption of a Markov process is not valid, because Y influence the transition of system X.

$$T(Y \to X) = \sum_{X_{t+1}} \sum_{X_t} \sum_{Y_t} p(x_{t+1}, x_t, y_t) \log \frac{p(x_{t+1} \mid x_t, y_t)}{p(x_{t+1} \mid x_t)}$$

Where the sums are over all amplitude states, and the index $T(Y \to X)$ indicates the influence of Y on X. The transfer entropy is explicitly asymmetrical under the exchange of X and Y — a similar expression exists for $T(X \to Y)$ — and can thus be used to detect the directed exchange of information (e.g., information flow, or causal influence) between two systems. As a special case of the conditional Kullback-Leibler entropy, transfer entropy is non-negative, any information flow between the two systems resulting in $T>0$. In the absence of information flow, i.e., if the state of system Y has no influence on the transition probabilities of system X, or if X and Y are completely synchronized, $T(Y \to X)=0$ bit.

For our experiments, we used the iCub active vision head, which is endowed with two cameras whose movements are decoupled and need to be coordinated in order for the robot to sample usable information from the environment. The attention system is in charge of selecting the orientation of both cameras in such a way that good information structure can be induced in the sensory-motor stream. From the literature we know that in the first few months of life, human infants develop characteristics features of the attention system such as vergence and smooth pursuit tracking. The questions we addressed are the following ones. (1) What mechanisms are responsible for the development of vergence and smooth pursuit? (2) Which are the key features that we have to take in account to reproduce these mechanisms and the ensuing behaviours on the iCub? And (3) how can these principles be applied to more challenging tasks such as grasping.

Our main hypothesis is that the sensor morphology restricts the possible set of actions that yield a high level of information structure. Such structure is important because without it the robot is not able to learn and without learning the robot cannot predict future sensory inputs or relations among signals, which in the end is the main purpose of a vision system. The two basic elements of our framework were inspired by nature, and are the following ones: (1) the combination of the left camera and right camera in one binocular single image; and (2) non-uniform sampling of the pixels in the image using a log polar transformation. The parameter *M* was used to increase or decrease the amount of pixels used in the log-polar space

$$\rho(x, y) = M \cdot \log(\sqrt{x^2 + y^2})$$
$$\phi = \arctan(y / x)$$

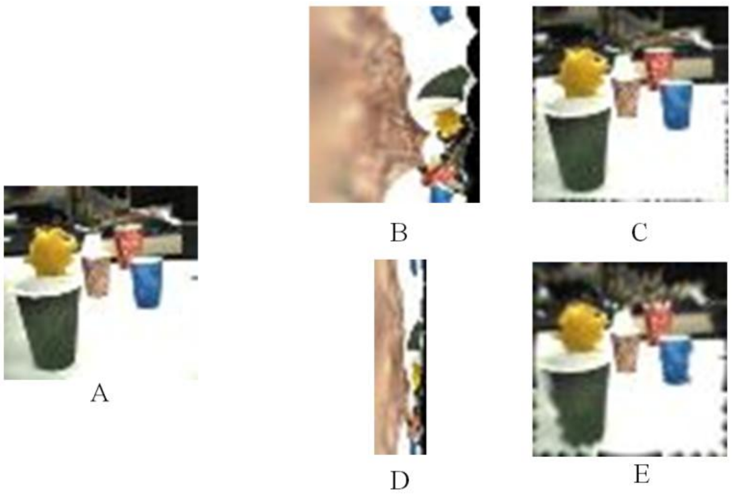

Figure 14: Log-Polar Transform of 60X60 Image. (A) Raw image. (B) Log-polar transform with *M=20*. (C) Inverse log-polar transform. (D) Log-polar transform with *M=12*. (E) Inverse log-polar transform.

To perform our experiments we implemented two image processing modules, a tracker and a disparity map. With these we developed three experiments. (1) The robot was looking at a fixed area and a rotation cup was crossing its field of view. (2) The robot was tracking the rotating cup, and (3) the robot was looking at different cups in a specific sequence. Extensive information theoretic analyses of the collected time series show that the average of both images (which gives a binocular single image) restricts the information structure not just among pixels but also among pixels and actions in the vergence area.

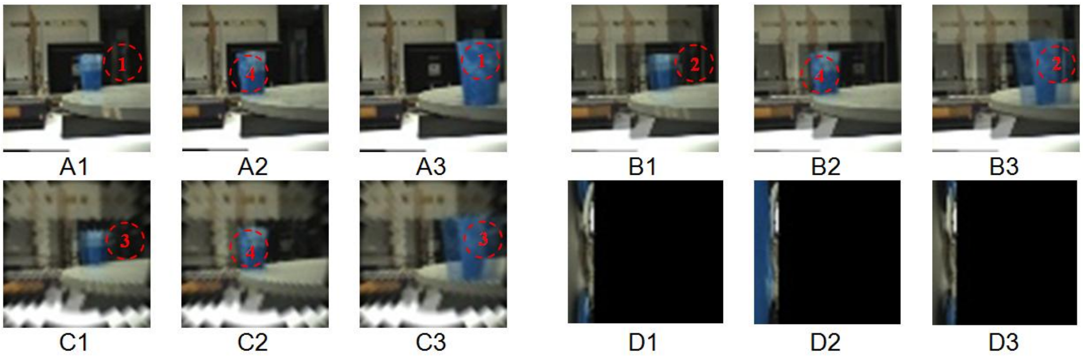

Figure 15: Data from the Experiment (1). These are the frames saved in the experiment, they show a cup on a rotating table that is coming from behind and going out to the front. (A) The frames from the left camera. (B) The average images from the left and right. (C) Average inverse log polar transform. (D) Average log polar transform. (1) The pixels far from the centre (e.g. dotted circle) have less information structure than the pixels in the centre because the object is changing the size in the image for the rotation. (2) The average between left and right images, introduce a distortion in the pixels that are not in the vergence area (e.g. dotted circle). (3) The log polar transform has less receptors far from the centre increasing the distortion outside the centre (e.g. dotted circle). (4) The centre is not affected by the log polar transform neither for the average because the object is in the vergence region (e.g. dotted circle).

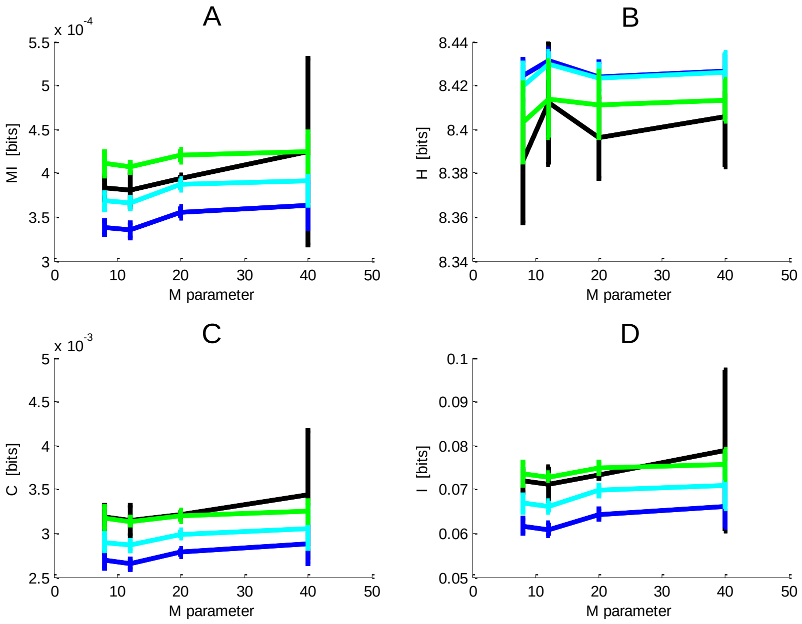

Figure 16: Results Experiment (1). In the figures A to D green is the right camera, black is the left camera, cyan is the average of both images and blue is the Average inverse log polar transform (A) Mutual information (B) Entropy (C) Complexity (D) integration.

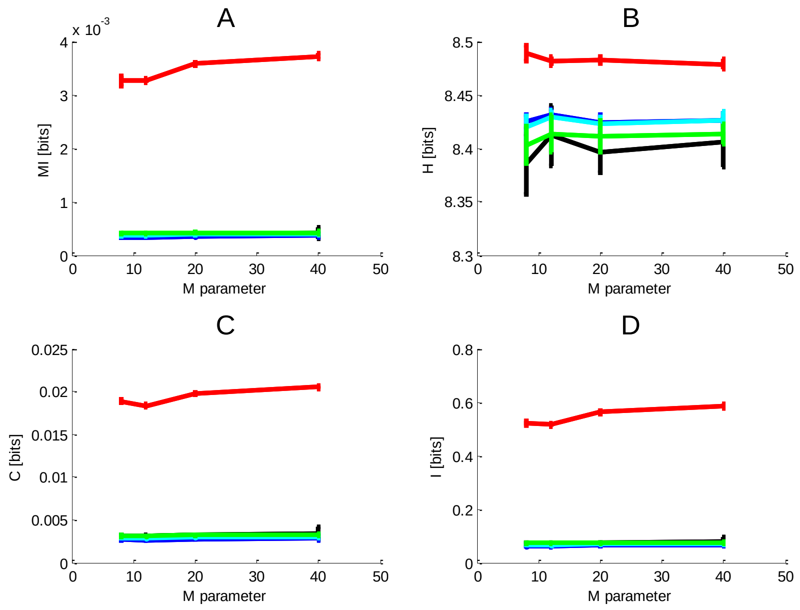

Figure 17: Log Polar Pixels Information Structure from Experiment (1). In the figures A to D green is the right camera, black is the left camera, cyan is the average of both images, blue is the Average inverse log polar transform and red is the average log polar transform (A) Mutual information (B) Entropy (C) Complexity (D) integration.

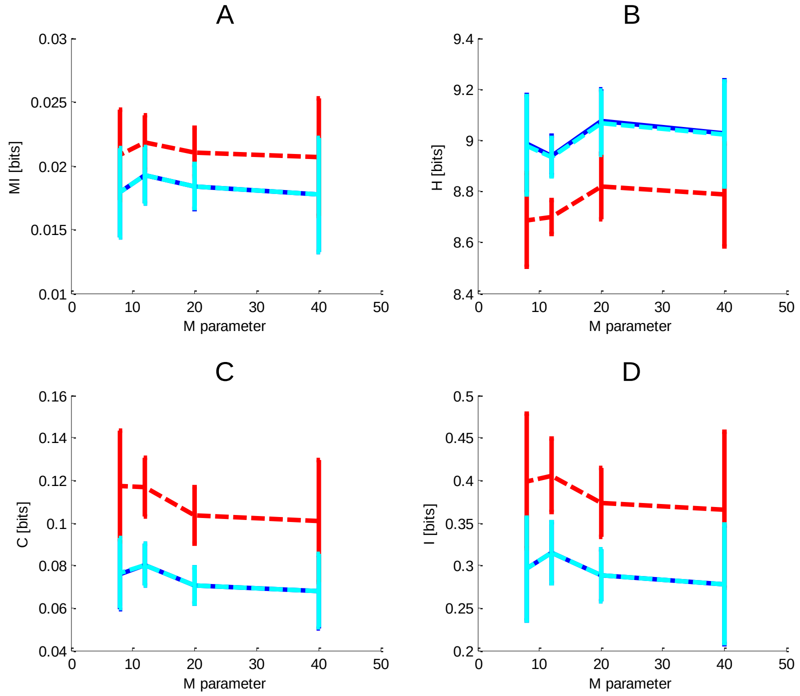

Figure 18: Results Information Structure Pixels and Encoders Experiment (2). In the figures A to D cyan is the average of both images, blue is the Average inverse log polar transform and red is the average log polar transform (A) Mutual information (B) Entropy (C) Complexity (D) integration.

We infer that the log-polar transform samples the image in such a way that, without damage to the overall structure, a smaller amount of pixels carries more good information structure. Consequently, the learning process of the agent improves because although there are a lower number of inputs, more associative relations in the sensory stream are induced. Finally, control is required to coordinate the previous mechanisms, forcing a higher density of receptors in the area of vergence, and the better the control is, the higher the causal relations among actions and pixels.

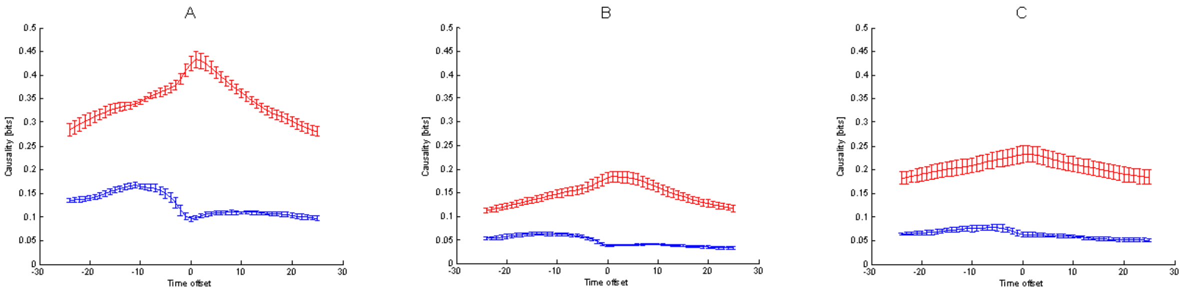

Figure 19: Causality Results with Different Controllers in Log Polar Image M Parameter Equal to 8 in the Experiment (3). In the figures A to C appears the average per pixel of the 3DOF causality summation, blue is the sensor to motor and red is motor to sensor (A) Controlling all the 3DOF (B) One camera is tracking while the second one is moving in the same way (C) adding noise to the motion of the camera

These results are relevant because they show that an appropriate morphology not only decreases the complexity of the processing problem, but also induces "richer" input streams enabling the agent to learn faster and make better predictions. In order to enable the development of the controller through the interaction we can use, on the one hand, the information measures over the sensory-motor stream, however, this requires the calculation of multidimensional probability density functions which are computationally expensive requiring large number of data points for their estimation. On the other hand, we can use directly a measurement of the prediction quality that at the end is the agent's objective function.

The approach described above represents a new alternative to model the development of disparity learning, an ability that develops in human infants in the first few months of life, but has to our knowledge not yet been modelled as an unsupervised process in an artificial robot head. In future work, we will present an innovative approach where the sensory morphology constrain the possible set of actions, which allow the agent predict new sensory inputs. This "intrinsic motivation" of prediction and understanding is what pushes the development of vergence and therefore the intrinsic knowledge of disparity.

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UNIUP

UNIUP has been working along five different lines of investigation.

Action understanding – We asked whether other people's actions understood by projecting them onto one's own action programs and whether this mode of control is functioning in infants. Adults' and infants' gaze and hand movements were measured in two live situations. The task was either to move an object between two places in the visual field, or to observe the corresponding action performed by another person. When the subjects performed the action, infants and adults behaved strikingly similar. They initiated the hand and gaze movements simultaneously and gaze arrived at the goal ahead of the hand. When observing such actions, the initiation of the gaze shifts was delayed relative to the observed movement in both infants and adults but gaze still arrived at the goal ahead of the hand. The infants' gaze shifts, however, were more delayed at the start, less proactive at the goal, and showed kinematic variability indicating that this mode of functioning is somewhat unstable in 10-month-old infants. In summary, the results showed that both adults and infants perceive the goal of the action and move gaze there ahead of time, but they did not support the idea of a strict matching of the kinematics between the eye movements carried out when performing and observing actions.

Spatial knowledge – Two studies on infants' understanding of spatial relationships between objects were finished and published during the period. In the first one we investigated infants ability to choose the right size and form of an object to be inserted into an aperture (European Journal of Developmental Psychology). In the other one 3 experiments were reported that investigated changes from 15 to 30 months of age in children's (N = 114) mastery of relations between an object and an aperture, supporting surface, or form. When choosing between objects to insert into an aperture, older children selected objects of an appropriate size and shape, but younger children showed little selectivity. Further experiments probed the sources of younger children's difficulty by comparing children's performance placing a target object in a hole, on a 2-dimensional form, or atop another solid object. Together, the findings suggest that some factors limiting adults' object representations, including the difficulty of comparing the shapes of positive and negative spaces and of representing shapes in 3 dimensions, contribute to young children's errors in manipulating objects (Child Development).

Predictive actions – A study investigating infants ability to reach predictively for a rotating rod was finished and published. Hand adjustments of 6- and 10-month-old infants and adults were studied as they reached to grasp a rotating rod. It was found that the subjects in all three age groups adjusted the hand prospectively to the rotating rod during the approach of it. They also adjusted the reaches to the rotating rod in such a way that almost all of the grasps were overhand ones as predicted by the endpoint comfort hypothesis. Finally, it was found that the rotation of the hand was made up of movement units as translational movements are, and that the approach units were relatively independent of the rotational ones (Zeitschrift für Entwickelungspsychologie und Pädagogische Psychologie).

Eye-neck coordination – A study of eye-neck coordination in the icub was finished in collaboration with IST. We described a method for the coordination of eye and neck motions in the control of a humanoid robotic head. Based on the characteristics of human oculomotor behavior, we formulated the target tracking problem in an state-space control framework and show that suitable controller gains can be either manually tuned with optimal control techniques or learned from bio-mechanical data recorded in human subjects. The basic controller relies on eye-neck proprioceptive feedback. In biological system, vestibular signals and target prediction compensate for external motions and allow target tracking with low lag. We provide ways to integrate inertial and prediction signals in the basic control architecture, whenever these are available. We demonstrate the ability of the method in replicating the behavior of subjects with different ages and show results obtained through a real-time implementation in a humanoid platform (ICDL2009).

Sensorimotor development in premature children – Studies of eye tracking and reaching in very prematurely born infants (before week 32 GA). The effects of premature birth could either enhance the developments of basic functions by providing access to the external environment at an earlier age, or corrupting these developments by interrupting the access of basic nourishments and other supports from the intra-uterine environment. Smooth pursuit eye tracking and reaching for moving objects were studied in 113 premature infants The basic results show that premature birth obstructs the development of both these basic functions but that experiential factors will help the infants to regain them later on. These studies are of crucial importance for the understanding of the interaction between biological and experiential factors in early development (manuscripts 9-12).

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UNIFE

The main aim was to study and model the development of sensorimotor coordination and sensorimotor mapping. UNIFE was particularly involved in addressing the ontogenetic cues for sensorimotor coordination.

Task 3.1: Modelling the ontogenesis of gaze control and eye-head coordination, for example to study and model oculomotor involvement in orienting of visuospatial attention and visuomotor priming in object-directed actions.

In order to study and model oculomotor involvement in orienting of visuospatial attention, UNIFE and IST collaborated to perform an experiment based on recent behavioural data indicating that gaze direction triggers reflexive shifts of attention toward the gazed-at location.

We decided to investigate the efficiency of directing attention determined by the robot gaze in comparison to real human gaze, to face drawing gaze, and to arrow pointing. Moreover, differently from what previously done in literature, the to-be-responded target was an LED not lying on the same plane as the cue, but in the space between the cue and the subject. Two are the main goals of the experiment. The first one concerns the comparison of effectiveness in orienting of attention between the drawing of a schematic face apparently moving its eyes, and the real face of an experimenter seated in front of the subject and directing his gaze. In literature, only schematic drawings, or static face pictures have been used. The second goal addresses the way in which individuals consider the iCub: is it considered more similar to the drawing of a schematic face or to a real human face? In other words, is the effectiveness in orienting of attention determined by the direction of the iCub gaze, more similar to that obtained by observing gaze direction in a schematic face or in a human face?

In order to answer these questions we performed an experiment in which participants were required to press a button as soon as an LED placed on their right or on their left was switched on (see the figure below).

Before the appearance of the imperative stimulus, four different experimental situations, each of them presented separately in different experimental sessions, could be presented:

1. a central horizontal arrow pointing either towards the left or towards the right;
2. a schematic face with its eyes deviated either towards the left or towards the right;
3. the iCub directing its gaze towards the left or towards the right;
4. the experimenter directing his gaze towards the left or towards the right.

During the last year we decided to slightly modify the experimental set-up with respect to that reported in the previous periodic report in order to simplify it and to really focus our study on the sharing of attention on the target position between participant and experimenter/robot. Consequently, we changed the position of the target and we considered the intervals between cue and target presentation only of 200 ms. Finally, we introduced catch trials (cue present, target absent: the participant has to refrain from responding) to ensure that responses are based on target detection and not triggered by cue appearance.

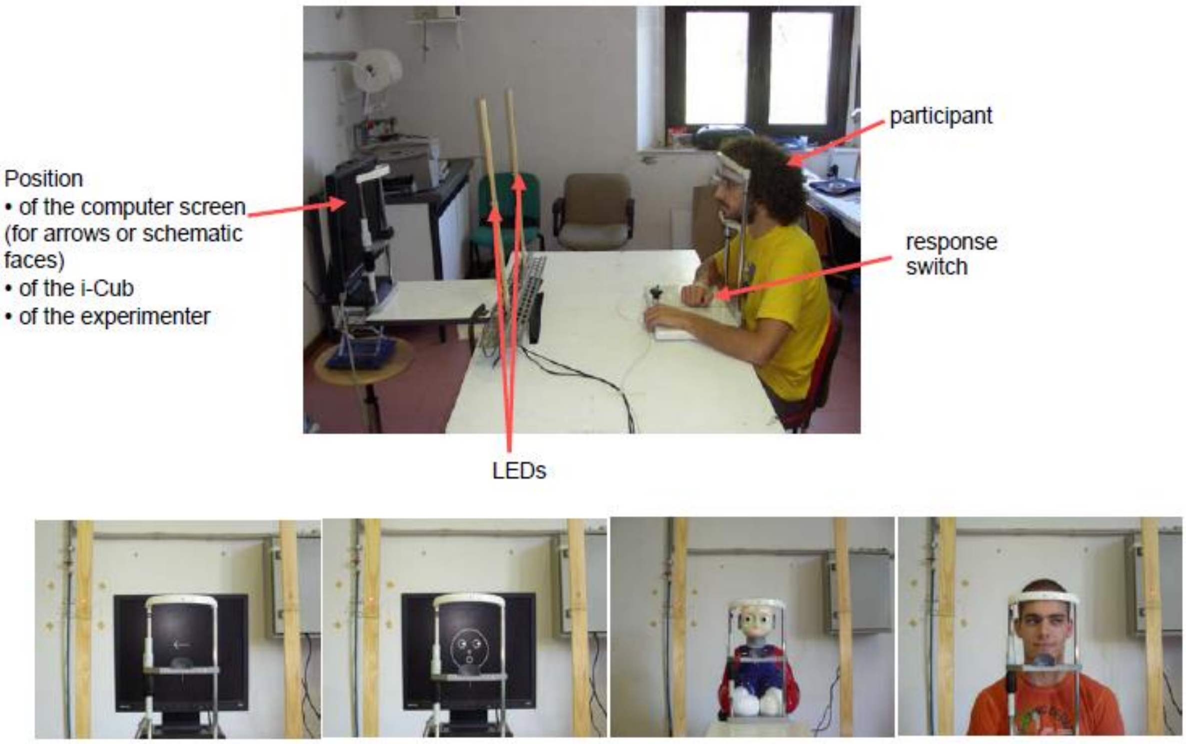


Figure 20: Experiment where participants were required to press a button as soon as an LED placed on their right or on their left was switched on (see text for details).

Results (see Figure 22) indicated that all the four types of cues determine an orienting of attention towards the cued hemifield. However, there was a significant difference between reaction times in response to human and schematic face cues and a tendency to a significant difference between human and arrow as well as robot cues.

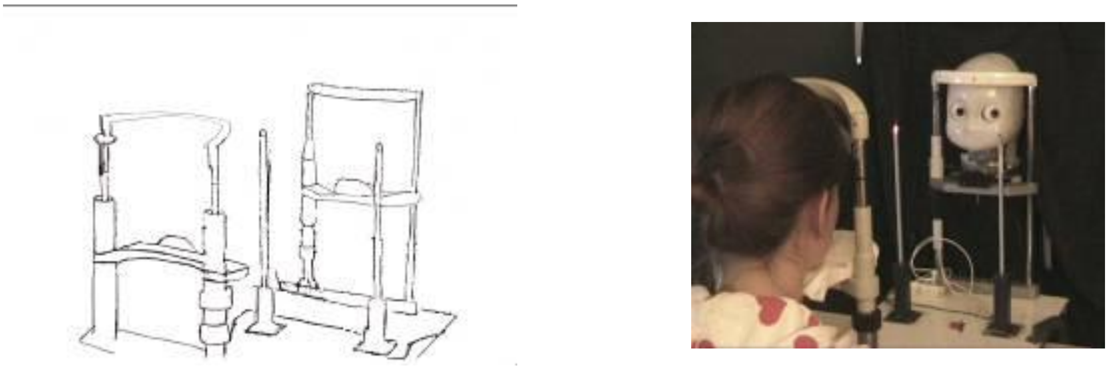


Figure 21: The experimental setup.

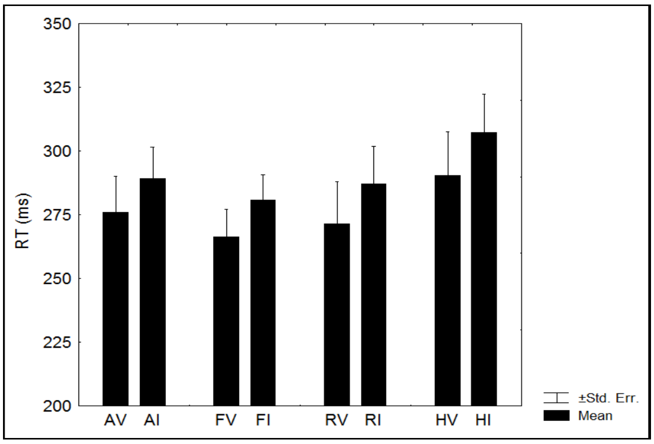


Figure 22: A (arrow); F (schematic face); R (robot); H (human)

Therefore, present results suggest that a schematic face and the iCub face as well are considered different from the real human face. Present paradigm, therefore, could be useful in testing the efficacy of future more developed robot aspect or behaviour to determine the same effects of a real human face.

Task 3.2: Modelling the ontogenesis of functional reaching and grasping of arm-hand cooperation (Grasping - haptic) to study aspects such as how to predict reaching/grasping outcomes and how to code action goals.

(a) We previously reported an experiment testing the ability to predict the instant at which a grasping hand touches an object. To this purpose we presented subjects with two different grasping actions: the one most suitable for the presented object and a less appropriate one. Subjects were required to detect the instant at which the demonstrator's hand touched the object. In a further condition, subjects were required to detect the outcome of an action performed by a robotic arm moving with constant kinematics. Results showed that while in the case of robot grasping subjects responded before the touch instant, in the case of human grasping the response followed the touch instant, but occurred much earlier than simple reaction times. This demonstrates that subjects were able to predict the outcome of the seen action. The predictive capability was specifically enhanced during observation of the "suitable" grasping. We interpreted these results as an indication of the synergic contribution of both object-related (canonical) and action-related (mirror) neurons during observation of actions directed towards graspable objects.

In a further work we wanted to challenge the hypothesis that the facilitation in the responses is determined by the contextual constraints limiting the observed grasping execution (in this case, biomechanical constraints), and not possibly due to a faster visual recognition of a particular hand posture configuration. To this purpose, the same paradigm used by Craighero et al. (2008) was used, but responses to the same grasp were compared when observed to take an object and to take that same object rotated of 90°, consequently requiring a different hand-object interaction to be efficiently grasped. To further test this hypothesis, we wanted to verify if also the hand used by the agent influences the detection. To this purpose, the agent grasped the object by using either her right or her left hand, but the position of the object was such that the difficulty in grasping execution was the same for both hands.

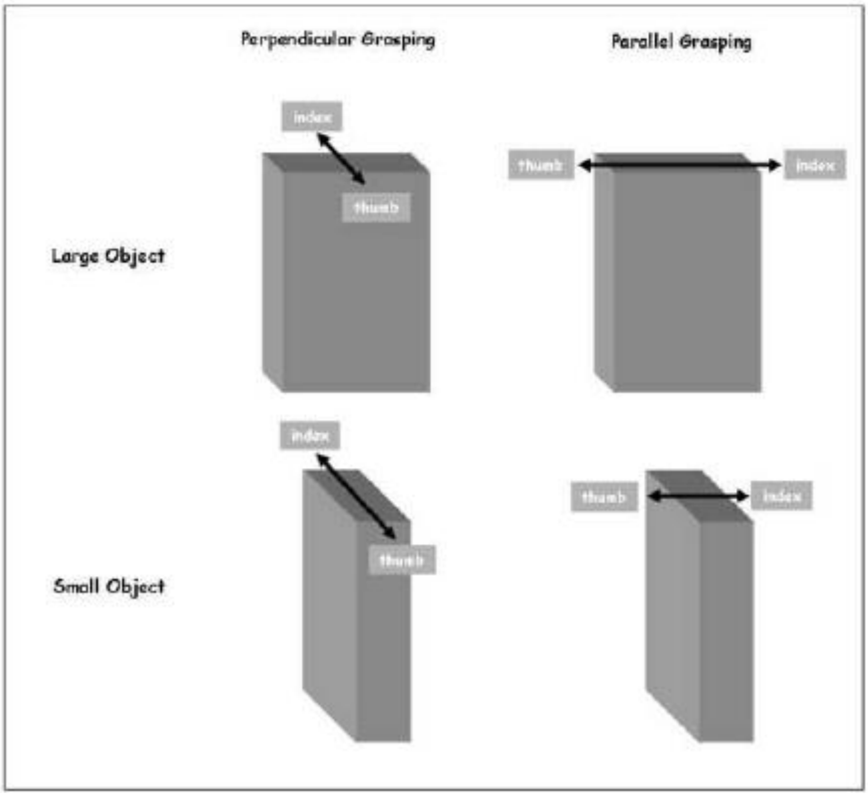


Figure 23: Schematic representation of the object orientation in the two sessions (Large Object, Small Object), and of the type of grasping used by the experimenter (Perpendicular Grasping, Parallel Grasping) in each session. The arrow represents the finger's opposition space, and the labels 'thumb' and 'index' refer to the position of these fingers from the experimenter's perspective when using her right hand for grasping. When using her left hand, the position of the thumb and index finger were inverted, but only regarding the Parallel Grasping.

Results confirmed those found by Craighero et al. (2008) regarding the large object, and confirmed that the detection of the time-to-contact (mean=70 ms) was faster than usual simple reaction times (usually not faster than 100-120 ms). Finally, the statistical significance of the interaction indicates that responses to the same grasping are modulated by the to-be-grasped object, and that different objects' physical properties facilitate the detection of the time-to-contact of different types of grasping.

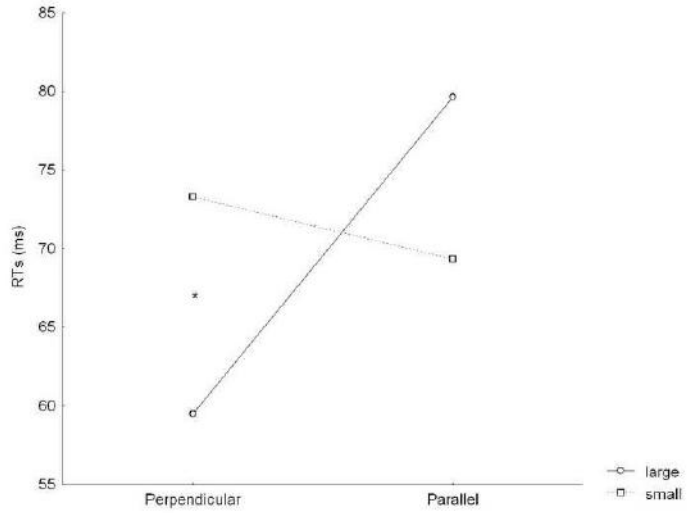
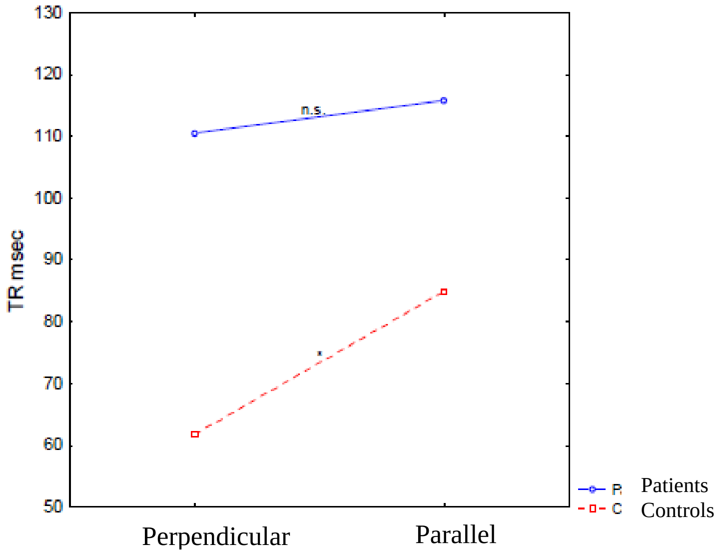


Figure 24: Response times (RTs; time-lag between the instant at which the demonstrator touched the object with either index finger or thumb and the instant at which the participant touched the pad) for Perpendicular and Parallel grasping towards the Large and the Small object are shown.

In order to verify if the involvement of the motor system is causal for action observation, a simplified version of the same task was submitted to 14 hemiplegic patients matched with normal controls. Only Large object was presented. Results indicated that hemiplegic patients did not show any difference in reaction times between suitable (Perpendicular) and not suitable (Parallel) grasping observation, strongly suggesting that the actual possibility to execute observed actions has an important role in action detection.



(b) Functional brain studies showed that the human mirror system responds similarly to the primate mirror neuron system, and relies on an inferior frontal, premotor, and inferior parietal cortical network. Furthermore, this mirror system is more activated when subjects observe movements for which they have developed a specific competence or when they listen to rehearsed musical pieces compared with music they had never played before. Though humans rely greatly on vision, individuals who lack sight since birth still retain the ability to learn actions and behaviours from others. To what extent is this ability dependent on visual experience? Is the human mirror system capable of interpreting nonvisual information to acquire knowledge about the others?

The mirror system is also recruited when individuals receive sufficient clues to understand the meaning of the occurring action with no access to visual features, such as when they only listen to the sound of actions or to action-related sentences. In addition, neural activity in the mirror system while listening to action sounds is sufficient to discriminate which of two actions another individual has performed. Thus, while these findings suggest that mirror system may be activated also by hearing, they do not rule out that its recruitment may be the consequence of a sound-elicited mental representation of actions through visually based motor imagery.

We used functional magnetic resonance imaging (fMRI) to address the role of visual experience on the functional development of the human mirror system. Specifically, we determined whether an efficient mirror system also develops in individuals who have never had any visual experience. We hypothesized that similar mirror areas that further process visually perceived information of others' actions and intentions are capable of processing the same information acquired through nonvisual sensory modalities, such as hearing. Additionally, we hypothesized that individuals would show a stronger response to those action sounds that are part of their motor repertoire.

To this purpose, we used an fMRI sparse sampling six-run block design to examine neural activity in blind and sighted healthy volunteers while they alternated between auditory presentation of hand-executed actions (e.g., cutting paper with scissors) or environmental sounds (e.g., rainstorm), and execution of a "virtual" tool or object manipulation task (motor pantomime).
Results show that in congenitally blind individuals, aural presentation of familiar actions compared with the environmental sounds elicited patterns of neural activation involving premotor, temporal, and parietal cortex, mostly in the left hemisphere, similar to those observed in sighted subjects during both aural and visual presentation.

These findings demonstrate that a left premotor–temporo-parietal network subserves action perception through hearing in blind individuals who have never had any visual experience, and that this network overlaps with the left-lateralized mirror system network that was activated by visual and auditory stimuli in the sighted group. Thus, the mirror system can develop in the absence of sight and can process information about actions that is not visual. Further, the results in congenitally blind individuals unequivocally demonstrate that the sound of an action engages human mirror system brain areas for action schemas that have not been learned through the visual modality.

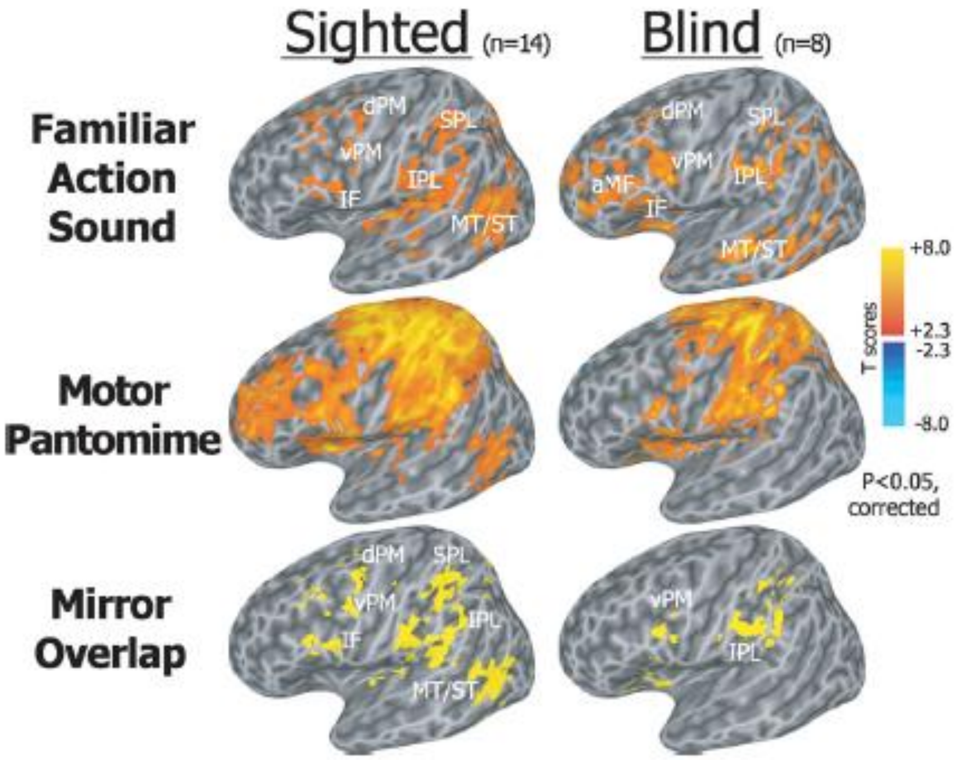


Figure 25: Statistical maps showing brain regions activated during listening to familiar action compared with environmental sounds, and during the motor pantomime of action compared with rest (corrected p<0.05). In both sighted and congenitally blind individual, aural presentation of familiar actions compared with the environmental sounds elicited similar patterns of activation involving a left-lateralized premotor, temporal, and parietal cortical network. Hand motor pantomimes evoked bilateral activations in premotor and sensorimotor areas. Auditory mirror voxels are shown in yellow as overlap between the two task conditions in the bottom row. Spatially normalized activations are projected onto a single-subject left hemisphere template in Talairach space.

Task 3.10: Electrophysiological study of human sensorimotor representations.

This is an ambitious and promising project which associates fMRI on individual patients, electrophysiology and neuropsychological testing. The present study starts from the unique opportunity that derives from collaboration between the Neurosurgery Division of Udine Hospital, the Ferrara University and the Italian Institute of Technology, to study the border of brain cancers by electrophysiological techniques (i.e., single neurons). The possibility to record single neuron activity in awake humans will give essential elements to reveal the intimate mechanisms of sensorimotor integration in humans: before surgery, patients are investigated by using functional magnetic resonance imaging (fMRI) and high resolution electroencephalography (hr-EEG), during sensorimotor and cognitive tasks that are specifically selected according to the lesion site (e.g., if the lesion is located close to the hand representation of the primary motor cortex, the task will require hand mobilization, sensory stimulation, hand action observation, etc.). During surgery, similar tasks are performed by the patients (during single unit recordings) giving therefore the terms for the comparison between results arising from the different techniques. Our aim is to provide physiological data about cortical areas that until now have been rarely studied with microelectrode-based electrophysiological techniques. This is because, in our approach, neurophysiology is at the service of the patient: intracortical recordings of single neuron activity in patients with low-grade gliomas allow determining the functional border between pathological and normal brain tissue. In the specific case of low-grade lesions it is mandatory to define an acceptable compromise between the extension of the surgical ablation (that determines *quod vitam* prognosis) and the possible consequent functional deficit (that determines *quod functionem* prognosis). For these reasons, the Ethical Committee of Udine Hospital has expressed a positive judgment about this project and its finalities. Results from this task, especially the technology and some preliminary results of the recording, are described in a specific deliverable D3.7 (Preliminary Data on Human Electrophysiology).

IST

The work developed by IST in this Workpackage concentrated in the following main directions: (i) learning controllers for eye-neck coordination from human recordings; (ii) body schema learning using active exploration strategies to improve learning; and (iii) integrating 3D models based tracking method in the software architecture to enable robust perception of objects.

Learning eye-neck controllers – A model of eye-neck coordination using coupled controllers was developed jointly with the University of Uppsala. Such a controller is able to model adequately the human saccade behavior, whereby the eyes move very quickly to the target, then the neck follows and the eyes counter-rotate to the keep the image stable on the retina. Likewise, the controller also models some aspects of the smooth pursuit behavior where the neck lags the eyes. The structure of the controller allows the learning of its gains from human data recordings. This way it was possible to achieve, up to the limits allowed by current technology, to performance similar to infants.

Biomimetic Eye-Neck Coordination. Manuel Lopes, Alexandre Bernardino, José Santos-Victor, Claes von Hofsten and Kerstin Rosander. IEEE - International Conference on Development and Learning, Shanghai, China, 2009.

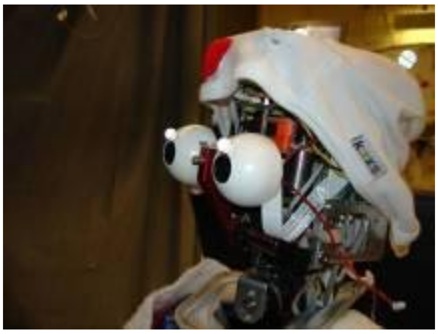


Figure 26: The iCub head following targets while the head-eye motion is being recorded (joint work IST – UNIUP and was later used for learning eye-neck coordination models.

Body schema learning – Following the line of research of robot self-calibration, we have developed a bio-inspired approach for calibration of serial robots, using proprioception and observation of end-effectors. We have focused on sequential learning of the body schema, which allows incorporation of new observations as soon as they are obtained and, at the same time, it allows to incorporate modifications, such us tool grasping. At IST, we have developed efficient estimation methods that outperform in terms of reliability and accuracy to the state-of-the-art calibration techniques. At the same time, we have developed active learning algorithms for body schema. These methods replace the random exploration of motor babbling with a selective sampling procedure, providing more informative motions and observations.

Ruben Martinez-Cantin, Manuel Lopes and Luis Montesano (2009) Active Body Schema Learning. In Robotics: Science and Systems, Workshop on Regression in Robotics.

3D models based tracking – The 3D model based tracking has been described already as part of Workpackage 2 since it lays in between the development of the Cognitive Architecture and the basic vision methods for robot control.

EPFL

In the last reporting period, EPFL has developed an architecture for the generation of discrete and rhythmic movements in which trajectories can be modulated by both high-level commands and sensory feedback information (Degallier et al, 2008, 2007, Righetti and Ijspeert, 2008). Our focus during this last period was on developing the interrelation between sensory feedback and high-level commands. For this, vision was included in the architecture and some new vision-based behaviours as reaching and navigation, were implemented both in simulation and on the real robot (in the air).

Progress with respect to the state of the art can be identified along two main lines of research:

- in controlling discrete and rhythmic movements, by developing an architecture that allows for the generation of both movements, so that a wide range of behaviours can be produced, from reaching to crawling, including drumming (Degallier et al, 2008).
- the study of infants crawling, through an extensive kinematic study of infants and the development of a control model for this type of locomotion (Righetti et al, 2008, Righetti et al, submitted, 2009).

Most of our work is in Task 3.6. The crawling controller that we have developed is based on the concept of CPGs that we take here as a low-level network of motor primitives used to generate complex trajectories given simple inputs. The motor primitives are implemented as coupled dynamical systems that can produce stable rhythmic and discrete trajectories. This low level controller has been enriched; it now includes four different simple behaviours:

- crawling;
- sitting/going on all fours;
- going on all fours (stop);
- reaching for a target object.

These different actions are used to implement a more complex behaviour where the robot moves towards a target object and reach for it while avoiding obstacles on its way. In order to so, a planner based on force fields is used to steer the robot towards the target and stay clear from the obstacles, whose location is acquired by vision. When the robot is close enough to a target object, it stops and reaches for it. For the reaching, we used the inversed kinematics module iKin that was developed at IIT. The whole crawling behaviour has been tested with a physics based simulator as well as on the real robot in the air (Deliverable 3.8). Tests of the architecture on the ground have brought to light some low-level control issues – interaction of the low-level integral controller with the higher level trajectory generation – on which the IIT team is currently working (at the moment of writing).

The transition from crawling to sitting (and vice et versa) has been successfully implemented in simulation, although it is not applicable to the real robot due to differences in the joint limits of the legs and arms.

In addition to the articles already accepted or submitted, several publications are under preparation, namely a conference paper on navigation and reaching, a journal paper on closed loop crawling, and another one on the whole architecture.

In Task 3.7 (superimposition of rhythmic and discrete movements), the same architecture was applied to drumming. The latter was recently enhanced by adding vision to the system. The drums can now be moved while the robot is drumming, the target position of the top of the stick being dynamically modulated to adapt to the changing environment. This demonstrates how our system for generating discrete and rhythmic movements can be used in real-time by higher-level control centres.

Righetti, L., Buchli, J. and Ijspeert, A.J, 2009. Adaptive frequency oscillators and applications. The Open Cybernetics & Systemics Journal. To appear

Degallier, S. and Ijspeert, A.J., 2009. Modeling Discrete and Rhythmic Movement through Motor Primitives: A Review, Submitted.

Righetti, L., Nylén, A., Rosander, K. and Ijspeert. A.J., 2009. Are crawling human infants different from other quadruped mammals? Submitted.

Righetti, L., Buchli, J. and Ijspeert, A.J., 2009. Dynamic Fourier series decomposition with adaptive frequency oscillators. Submitted.

USFD

The objective of the USFD research was to work in collaboration with the IIT to investigate the control architecture(s) that may enable improved control of gait in a humanoid iCub robot and to identify issues that arise in this design process due to robot dynamics, gait specification and control structure. In particular, no constraint is applied to inter-joint communications in order to assess whether or not decentralised control is inherently inhibiting. This problem is important as part of the important set of engineering questions pertaining to effective robot locomotion.

Planar Dynamic Equations

The goal of this work was to develop the planar dynamic equations for a generic humanoid robot with particular application to the iCub. Figure 27 shows the joint and torque sign conventions in the sagittal plane. A dynamical model of the iCub was developed assuming an open chain structure with the robot in its single support phase. Both Kane's and Lagrange's equations were used to develop the dynamical model. By taking two different approaches ensured that the resulting dynamical model was correct.

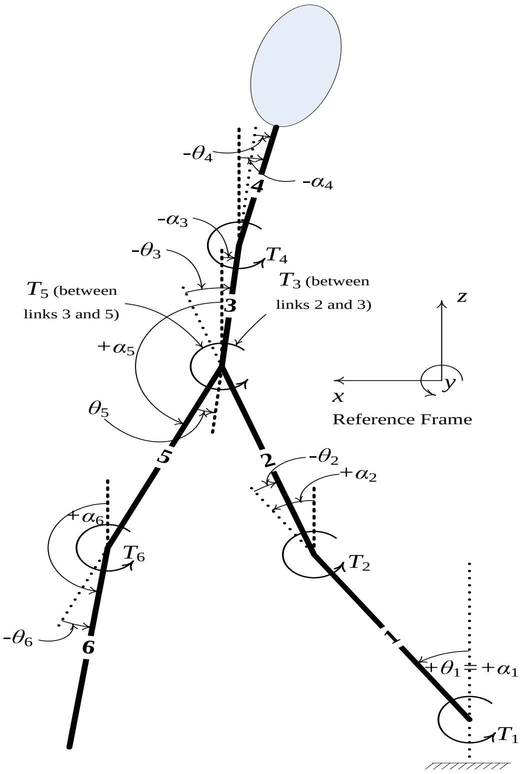


Figure 27: Sign conventions for the angles (absolute and relative) and torques used in developing the dynamic model.

Kane's equations provide an elegant formulation of the dynamical equations of motion. The basis of Kane's equations is that the sum of the generalised forces (both applied and inertial) for each generalised co-ordinate is zero. That is, for a mechanical system S having n degrees of freedom, represented by generalised co-ordinates q_r, Kane's equations state that

$$F_r + F_r^* = 0$$

where F_r and F_r^* are the generalised applied and inertial forces respectively corresponding to the co-ordinates $q_r, r = 1, \dots, n$.

Lagrange's equations provide a more traditional (but more cumbersome) approach to developing the dynamical model. Lagrange's equations for a holonomic system S with n degrees of freedom are given by

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}_r}\right) - \frac{\partial L}{\partial q_r} = F_r, r = 1, \dots, n$$

where F_r is the generalised force, and the Langrangian L is the difference between the kinetic energy K and potential energy P

$$L \triangleq K - P.$$

The resulting nonlinear dynamical model by applying Kane's or Lagrange's equations is not shown for brevity. Further work was undertaken to linearise the resulting equations for application to controller design.

Controller Design for Locomotion

For iCub biped walking, independent MIMO control systems are used for each plane (sagittal and lateral plane). Each control system includes position and velocity feedback, integral action (included to help overcome some stiction in the gearbox) and feedforward terms. These controllers ensure the stability of the biped robot for tracking any given trajectories. Any torque disturbances and measurement errors should be sufficiently rejected, this will make the control system quite robust. Besides the two MIMO controllers, there are two SISO controllers needed. These are responsible for keeping the swing foot parallel to ground (zero absolute angles) in both planes, they can be achieved by utilising simple position feedback. The structure of the first proposed controller is shown in Figure 28.

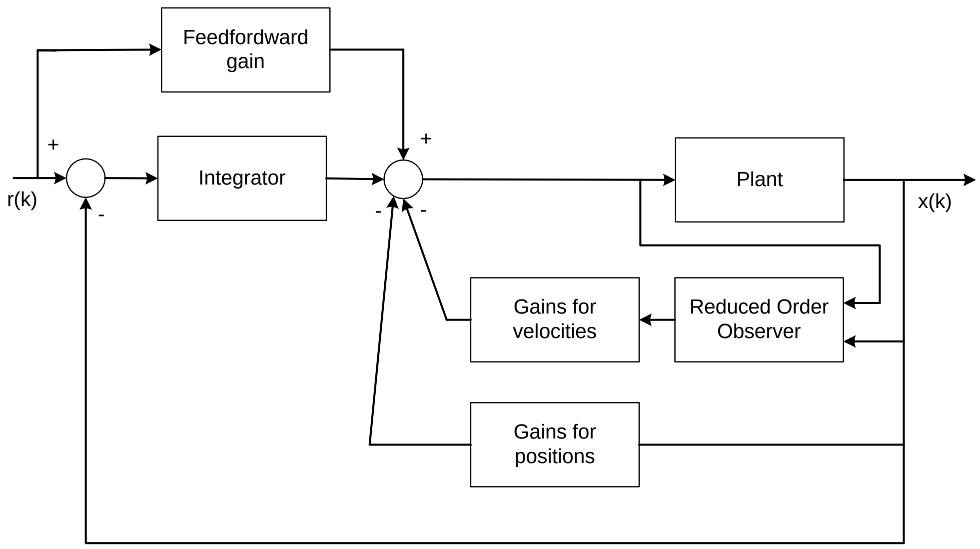


Figure 28: Initial controller structure for iCub locomotion.

Only relative angles of the iCub joints are measured, so in order to estimate the corresponding relative angular velocities, the design of a reduced order observer is necessary. In the design of the observer, torque disturbances and simple disturbances were neglected. This produces errors in the estimated angular velocities. However, despite state estimation errors, the performance of an observer-based controller can exhibit a good degree of robustness with respect to plant parameter variations. Here, obtaining a robust observer-based controller is more focused instead of the design of an observer with minimum estimation errors.

Linear Quadratic Regulator (LQR) technique was used to calculate the optimal state feedback gains. The plant model of both planes are controllable, therefore, the closed loop poles of the system can be placed at any location using state feedback gains. The structure of the control system is

$$u_{s(k)} = -L_s^2 x_{as}(k) - L_s^{11} x_{s1}(k) - L_s^{12} \hat{x}_{s2}(k) + L_s^{ff} r_s(k)$$

where L_s^{11} is the gain associated with the relative angles x_{s1}, L_s^{12} is for the relative angular velocities $\hat{x}_{s2}(k)$ and L_s^2 is for the integral action, x_{as} is the state vector for the integrators, r_s is the vector of filtered reference signals. The feedforward gain L_s^{ff} is set equal to L_s^{11}.

$$x_s(k) = \begin{bmatrix} x_{s1} \\ x_{s2} \end{bmatrix}$$

is the first 6 and x_{s2} is the remaining 6 elements of the state vector associate with relative positions and velocities respectively. The state space representation of the integral action is

$$x_{as}(k+1) = \Phi_{as}\, x_{as}(k) + \Gamma_{as}(k)$$

$$u_{as}(k) = r_s(k) - x_{s1}(k)$$

Here x_{as} is the state vector for the integrators and r_s is the vector of reference signals, which is set to zero in the LQR design. Φ_{as} and Γ_{as} are 6×6 identity matrices, x_{as}, r_s and x_{s1} are 6×1 vectors. The design of the optimal state feedback matrix starts with the specification of a quadratic performance index J and the constraint equation. The objective is to minimise J around the nominal operating point. The performance index is in the form

$$J_s = \sum_{k=0}^{\infty} (x_{ds}(k)^T Q_{ds} x_{ds}(k) + u_s(k)^T R_{ds} u_s(k))$$

where Q_{ds} and R_{ds} are chosen as diagonal matrices with positive entries. The constraint equation is (ignoring torque disturbances)

$$x_{ds}(k+1) = \Phi_{ds} x_{ds}(k) + \Gamma_{ds} u_s(k)$$

where:

$$x_{ds} = \begin{bmatrix} x_s \\ x_{as} \end{bmatrix}, \quad \Phi_{ds} = \begin{bmatrix} \Phi_s & 0_{12\times12} \\ -\Gamma_{as} C_s & \Gamma_{as} \end{bmatrix}$$

and $\Gamma_{ds} = \begin{bmatrix} \Gamma_s \\ 0_{6\times6} \end{bmatrix}$.

The selection of Q_{ds} and R_{ds} was investigated in MATLAB simulations and during experiments. The aims were to achieve fast response with little or no overshoot and to maintain the control signal within the power supplies limitation. The chosen values for Q_{ds} and R_{ds} are:

$$Q_{ds} = diag([Q_{sp}\ Q_{sv}\ Q_{su}])$$
$$Q_{sp} = diag([10^6\ 10^6\ 10^4\ 10^6\ 10^4\ 10^6])$$
$$Q_{sv} = 10^{-4} I_{6\times6}$$
$$Q_{su} = 10^{-1} I_{6\times6}$$
$$R_{ds} = I_{6\times6}$$

Here Q_{sp} is the matrix penalising angular positions, Q_{sv} is for the velocities and Q_{su} is for the integral actions. In selection of Q_{sp}, it is wanted as low as possible to prevent demands for large control actions. Low Q_{sp} values increase relative stability and reduce sensitivity to noise. However, to track reference signals with small errors and quickly attenuate torque disturbances, relatively high values of Q_{sp} are needed. Hence, the final value of Q_{sp} is a compromise between relative stability margins and the good tracking of reference signals. It is suggested that due to the fact that most of the oscillations originated in the hip joints, it is better to reduce the gains further in the hip joints by lowering the corresponding values for hip in Q_{sp} in order to dampen any oscillations.

In order to minimise the control efforts, Q_{sv} is set to a low value. In the sagittal plane, gains for integral actions are kept to minimum. High integral gains tend to cause oscillations in the system, mainly due to the presence of backlash.

Example locomotion trajectories were generated for static walking by solving the kinematic equations that define the location of the centre of gravity and the relative distance between the feet. For the robot to be in static balance, in the single leg support phase, the projection of the centre of gravity (COG) must be inside the support foot.

During double and single support phases, the swing foot is kept parallel to the ground at all times. In this way, the front and the rear of the swing foot is at the same height from the ground. This requirement is achieved by simply setting the absolute angles of the swing ankle joints to zero in both planes. Therefore, only set points for six joints in the sagittal plane and for four joints in the lateral plane are needed.

Figure 29 shows the tracking performance of the iCub robot. The simulation results indicate that reference signals are tracked very closely. However, since the locomotion is based on static walking trajectories the resulting walking speed is very low.

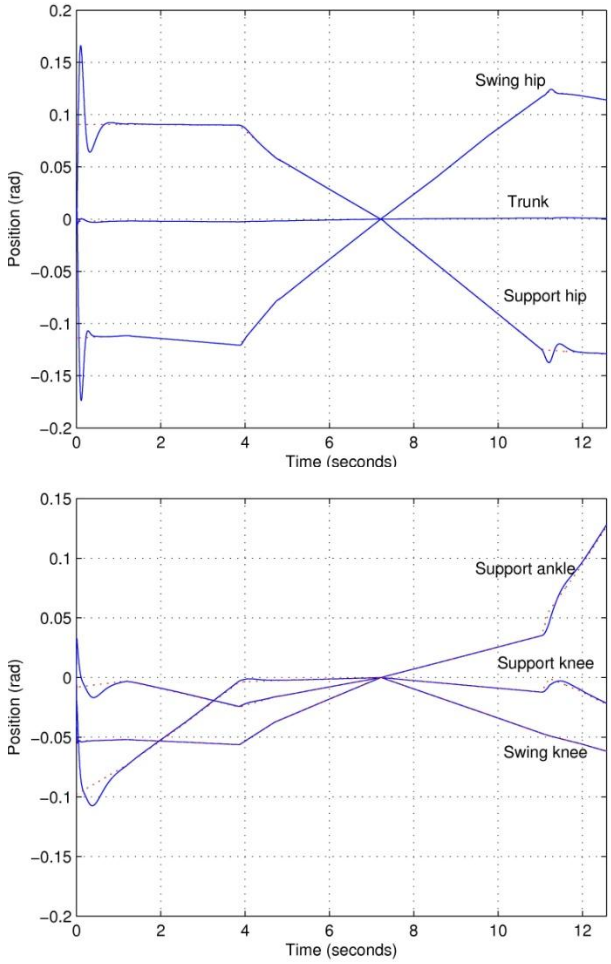


Figure 29: Tracking performance of the iCub robot in sagittal plane. Red dotted lines are the reference signals and the blue solid lines represent actual joint orientations.

Second Order Controller Design

The control scheme described above is very complicated. In this section, a novel second order design method is developed. Compared to the previous algorithm, this design method is much more systematic, and it is simple, easy to understand and implement. The second order design method addressed here can be separated into two stages. In Stage 1, a Proportional and Derivative (PD) compensator is chosen to let the plant possess desired dynamics. After that, in stage 2, by adding outer loop controllers, better trajectory tracking and stability properties can be achieved.

Design Stage 1

Consider a simple negative feedback control scheme shown in Figure 30 where the desired walking gait is r, and y is the actual iCub walking gait. The linearised iCub dynamic model can be expressed as a second order system:

$$G^{-1} = A_0\, s^2 + A_1\, s + A_2$$

Therefore, according to the control structure shown in Figure 4, the closed loop transfer function H_{cl} will be:

$$H_{cl} = (G^{-1} + C)^{-1}C$$

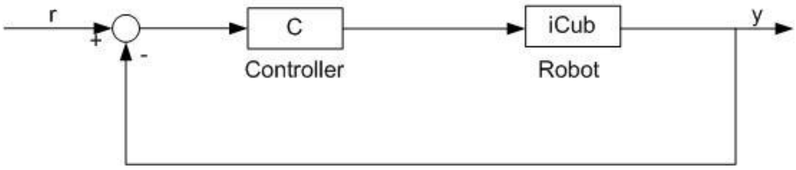


Figure 30: Simple feedback control structure for iCub bipedal locomotion.

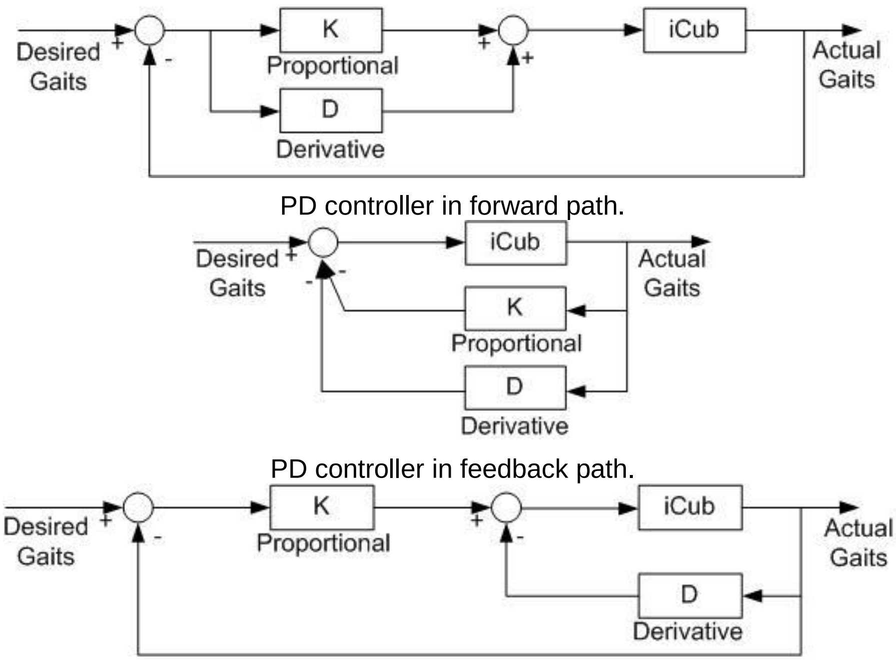
Now, assume that controller C is a simple PD controller with transfer function $C = K_p + K_d s$, then

$$H_{cl} = \left(s^2 + sA_0^{-1}(A_1 + K_d) + A_0^{-1}(A_2 + K_p)\right)^{-1} A_0^{-1}C$$

It is easy to see that the characteristic equation of this closed loop system has the same form as the characteristic equation of a standard second order system, $s^2 + 2\zeta\omega_{ns} + \omega_n^2 = 0$. Finally, with specified damping ratio ζ and natural frequency ω_n, the parameter of PD controller K_p and K_d can be determined by,

$$K_p = \omega_n^2 A_0 - A_2$$
$$K_d = 2\zeta\omega_n A_0 - A_1$$

Take a further investigation of the location of the PD controller, there are three possible places for the PD controller as shown in Figure 31.



Inner loop PD controller.

Figure 31: Three possible locations for the PD controller.

Comparing these three different structures and their transfer functions, although all of them have the same dynamics, it is clear that (c) is the best structure. First of all, the proportional gain in the forward path will give the system fast response to the error signal, and the derivative term in the minor feedback loop will reduce the overshoot. Secondly, if substitute $K_p = \omega_n^2 A_0 - A_2$ in (c) the effect of the interaction of the entire closed loop system can be ignored. Also, the designer can decouple the entire closed loop system by adding another compensator $K_p^{-1} A_0 \omega_n^2$.

It should be noted that without the integral term, constant steady state error is inevitable. In order to eliminate the steady state error, an additional controller is necessary.

Design Stage 2

The two major functions of the controller for iCub robot biped locomotion are:

1. Tracking the desired trajectories as accurate as possible;
2. Stabilised the entire system, avoiding iCub tip over or falling down.

The walking progress can be estimated as a periodic process, then the trajectory for different joint can be seen as a periodic signal. Therefore, Repetitive Control (RC) is a suitable control algorithm for this purpose. In this design stage, an RC controller is added. RC controller acts as an integral term to eliminate the steady state error. The overall control structure is shown in Figure 32.

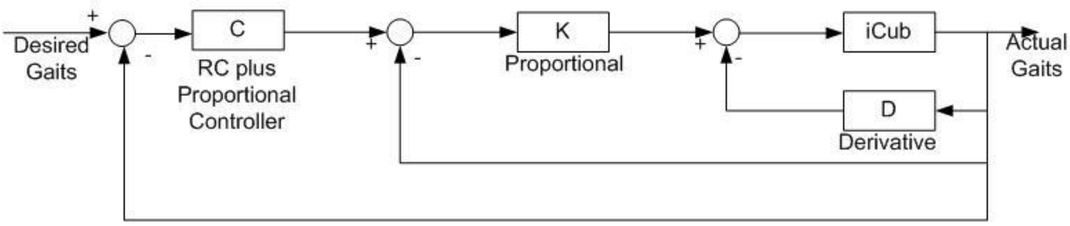


Figure 32: Second Order Design iCub bipedal locomotion control structure.

The joint based multivariable RC control algorithm is utilised here. For tracking N-periodic signal, the discretised control law is:

$$u(k) = q^{-N}u(k) + q^{-N}\beta\, G(q^{-1})^{*} e(k)$$

where $G(q^{-1})^{*}$ is the adjoint system of $G(q)$, β is the learning gain.

Static Walking Pattern Simulation

A more realistic reference gaits adopted here is obtained from (Winter, 2009). Compared to the static state walking gaits used before, these gaits are much smoother. One of the disadvantages is that the book only provides data for one and half period, so only one entire period data is gathered and duplicated for simulation, this may cause some problems. Another disadvantage is that the book only provides relative joint angles for ankle, knee and hip, but the simulation requires the angle of trunk. Refer to the static walking pattern, the angle of trunk is much smaller compared with other joints, hence, it is reasonable to assume that the relative joint angle for trunk is always zero.

The reference signals are filtered in order to eliminate the sudden changes between each point. The value of ω_n was determined from the spectrum of the reference signals to be ω_n=50 rad/s and furthermore $\zeta = 0.9$.

The tracking performance and the torques for the knee (the other joints demonstrate similar results) with PD controller are shown in Figure 33. The tracking performance is good with only some phase shift. By shifting the phase of actual gaits, it can be seen that the PD controller performs substantial tracking. Therefore, the PD controller is adequate if phase shifted reference tracking is acceptable. By applying

RC control algorithm, with $\beta = 1$, the tracking performance and the torques of the knee are shown in Figure 34.

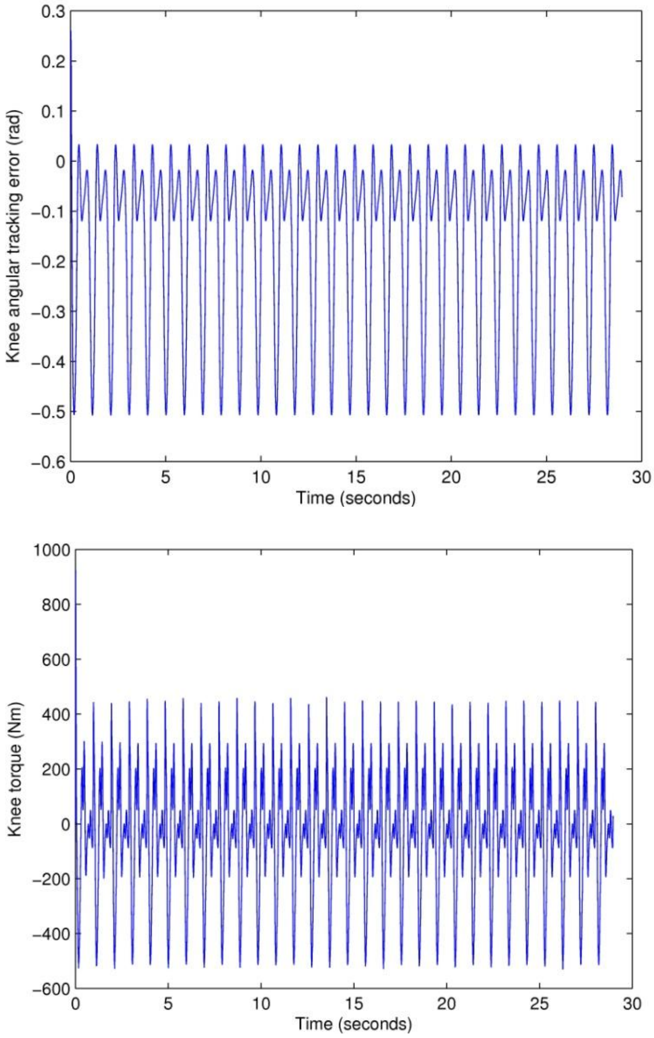
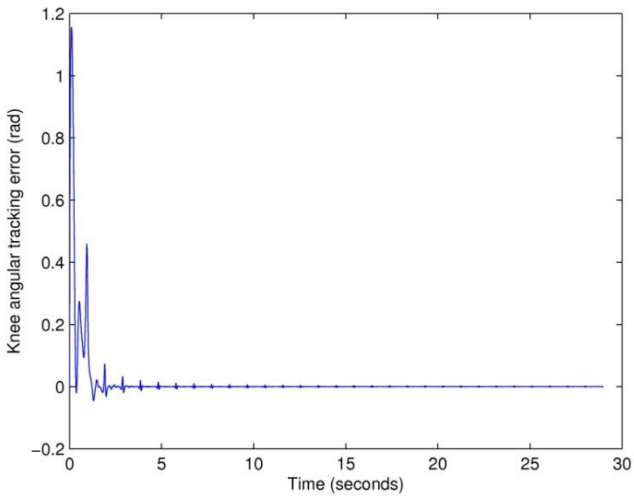


Figure 33: Tracking error and torque of human walking pattern with PD controller.



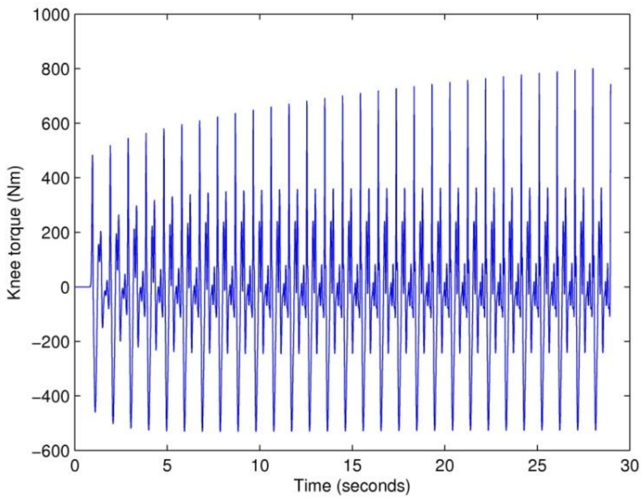


Figure 34: Tracking error and torque of human walking pattern with PD and RC controller.

The tracking performance of RC and PD controller are very good. After one or two steps, the tracking error goes down to zero. The reason is twofold. First of all, the initial condition of the iCub robot for walking is unknown, hence, it may need some time to achieve that condition. Secondly, the RC controller needs gather required information to start work, and it starts working after one step. The average value of torques for the two controller strategies are almost the same, for ankle, it is around 500Nm, for knee, it is about 400Nm, and for hip, it is 150Nm. The issue of high motor torques is common with humanoid gait control and is the subject of continued research.

References

Winter, D.A. (2009). Biomechanics and motor control of human movement. Wiley.

Deviations from the project work-programme

- An infant-like transition between crawling and sitting cannot be implemented on the iCub in its current format because of restrictive joint limits.
- Crawling has not been fully implemented on the iCub yet due to low-level control issues, on which the IIT team is currently working.
- Work of Task 3.6 focused on modelling of locomotion. In addition progress has been made towards the control of locomotion. Due to the complexity of developing the dynamical models and associated control algorithms it has not been possible migrating this work to the actual iCub robot or to investigate transitions between location and rest.

List of deliverables

Del. no.	Deliverable name	Workpackage no.	Date due	Actual/Forecast delivery date	Lead contractor
D3.6	Software implementation of the phylogenetic abilities specifically for the iCub &	3	65	65	UGDIST

	integration in the iCub Cognitive Architecture				
D3.7	Results from Electrophysiological study of human sensorimotor representations	3	60	65	UNIFE
D3.8	Demo of the iCub crawling and switching to a sitting position	3	60	65	EPFL

List of milestones

Milestone no.	Milestone name	Workpackage no.	Date due	Actual/Forecast delivery date	Lead contractor
M4.3	Release of version 2.0 of the iCub software	3	M65	M65	UGDIST

WP4 – Object Affordances

Workpackage objectives

The goal of this WP is that of exploring and modelling the mechanisms underlying the acquisition of object's affordances. This investigation can be seen developmentally as an extension of WP3. Specific models of how the primate's brain represents affordances will be considered (for example the parietal-frontal circuit) as well as results from psychological sciences. Note how much this is linked to aspects of sensorimotor coordination on one side (WP3) and of imitation and the understanding of goals on the other (WP5N). Specifically, we will investigate:

1. What exploratory behaviours support the acquisition of affordances, what is the relevant information (visual, haptic, motor, etc.)?
2. We will develop a model of the acquisition of object affordances and how the motor information enters into the description of perceptual quantities.
3. In analogy to what observed is in the brain, we will investigate how the definition of purpose (or goal) participates in the representation of the actions an object affords.

Active tasks

Task 4.1: Define roadmap of affordance-based experiments.
Task 4.2: Early affordant behaviours. Initial experiments will focus on self-exploration, to understand the development of the "basic" repertoire upon which an imitation system can develop. Successively the recognition of other individuals' actions will provide examples for acquiring new affordances.
Task 4.4: Software implementation for the iCub & integration in the iCub Cognitive Architecture.

Progress towards objectives

The term affordance was originally used by James J. Gibson to refer to all "action possibilities" on a certain object, with reference to the actor's capabilities. Thus, a chair is only "sit-able" for a perceiver of a certain height. However, whether an affordance is exploited by a perceiver or not has to do with the goals, values and interests of this perceiver.

Humans learn to exploit object's affordances through their entire lifespan but not all are learnt autonomously. A large set is conveyed by social means either by communication or by observing others actions. Due to the complexity of the human developmental process, it is difficult to separate the importance of learning by exploration and learning from others. Furthermore, learning from others may sometimes just be a question of highlighting a certain affordance. Notwithstanding, we distinguish two means of acquisition of object's affordances: that is, self-exploration (autonomous learning) and by observation (learning from examples). On a developmental perspective, it is natural to consider that self-exploration precedes the observation stage, though they are not simply sequential stages. Learning by observation requires some minimal capabilities, such as object and action recognition, in order to infer other agents' actions on objects, which are capabilities acquired by previous self-interaction with the environment. Therefore, for learning affordances, it is essential to be able to locate objects in the environment and execute goal-directed motor actions over objects. Much of the work in WP3 (sensorimotor coordination) focuses on the development of capabilities for controlling own actions which constitutes an important part of the primitives for the acquisition of object affordances. After the system has acquired the capability to coordinate movements with respect to sensorial information, it can start interacting with objects and understanding its interface – how to grab the object, what are the effects of certain applied actions. Then, the system may start recognizing and interpreting other agents interacting with similar objects, learning other object's affordances and interpreting activities. These capabilities have important relationship with the development of imitation and gesture communication (WP5N).

In the previous period we laid the foundations of affordances' acquisition (task 4.1 and 4.2). Here we show the latest results and their integration onto the iCub (task 4.3). These experiments were complemented by empirical research on the perception of objects in humans.

UGDIST/IIT

Affordances are the perceived action possibilities offered by the environment and building robots that can perceive them promise to be an important stepping stone towards cognitive robots. A recent example of the successful application of the affordance based approach in the domain of dexterous manipulation is given by the work of Montesano et al. (IST). Their work builds on the idea of using Bayesian Networks (BNs) to formalize affordances. These Bayesian Networks are learned to encode relationships between objects, actions and observed effects to one another. In related work, Metta and colleagues (past work previous to RobotCub) described a desirable affordance representation to be probability distributions over action primitives given an object. The current work at IIT first aims at replicating the positive results obtained by IST in the domain of grasping actions, then, the problem how the obtained Bayesian Networks can be used to derive probability distributions over action primitives is addressed. It could be shown that in general Bayesian Networks are a suitable formalism for deriving affordances from experience. However, how well these affordances reflect the acquired experience proved to depend heavily on the topology of the network. The results suggest that the taken method generalizes to more complex tasks, but also that it needs to be complemented with mechanisms for inducing goal-oriented behaviour in robots.

The reader is referred to (available from the RobotCub list of papers):

Ellmer, A. Probabilistic Modeling of Grasping Affordances in Robots using Bayesian Networks. Bachelor Thesis in Cognitive Science, Institute for Cognitive Science, University of Osnabruck, Germany.

for a complete description of the experiments. In the following a brief account of the main results is presented. Data for the experiments were collected with the iCub. A set of objects and primitive grasp types were used. In particular, the experimental protocol was as following:

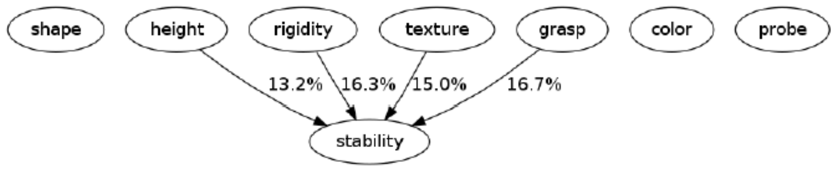
1 bringing the hand to the object
2 grasping the object with one of four different grasps
3 probing the object stability with one of two different moves
4 assessing the grasp stability
5 releasing the object
6 bringing the hand back to the starting position

Four actions, all considered primitives, were designed. In order to be better able to evaluate the affordance prediction capabilities of the resulting system, all four actions were pre-programmed and furthermore tailored to one specific reference object for which they should yield maximal stability. In addition to the grasp type, the second component making up an action that iCub applied to each object was a probing movement used to assess the stability of a given grasp/object combination. Two probing actions were implemented: probe encoding rotation of the forearm of approximately 150 degrees and “up and down” movement of the shoulder and elbow joint. As mentioned, the probing movement served to assess the stability of the grasp. Naturally, there are different possibilities for defining grasp stability. The most prominent measures for grasp stability are force and form closure and are drawn from an engineering perspective. Force closure and the related form closure are calculated by analyzing the forces exerted from the finger tips or the palm assuming certain friction coefficients and defining a stable grasp as one where arbitrary perturbations cannot alter the position of the grasped object. These measures, however, are unsuitable for our purposes. First, the geometric analysis and knowledge about friction coefficients are not an approach which would be considered valid in a developmental setting. Instead, it is desirable that the robot learns what stability refers to from its own experience, similar to a child who learns to associate certain actions with consequences on the external world, such as the pressure exerted on the palm while steadily holding an object. Unfortunately, the tactile sensors needed for this kind of measurements were not available on the robotic platform iCub. Thus, we could not make use of information provided e.g. by pressure sensors to infer the grasp stability. Instead, this information was provided from the outside, i.e. the experimenter categorized each performed grasp as stable, unstable, or failed. The objects were selected to represent a wide range of features, but only objects which were in principle – with one grasp or another – suitable to be held by iCub's hand were used for the final data collection. Each action, i.e. probe and grasp combination, was applied to each object between three and ten times. A total of 758 trials were collected.

Examples of the objects used in the experiments are shown in Figure 35.

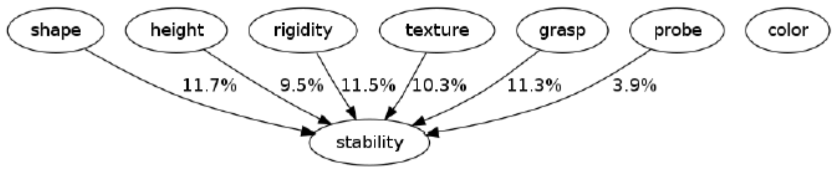
Figure 35: The set of objects employed for the experiments (see text for details).

In summary, in a first stage, data were used to learn the structure of the Bayesian Network using three different methods (for comparison): pure Dynamic Programming (DP) and a hybrid approach using DP to restrict the search space which is subsequently sampled using Markov Chain Monte Carlo methods (DPMCMC). Both of these approaches are subsumed under the notion of “DP methods" in the following. All algorithms here made use of interventional data, assuming perfect interventions. Structure learning using the K2 algorithm was also performed. K2 is a local, greedy search algorithm in the space of directed acyclic graphs. The results compared with manual design of the BN structure is shown below.



(a) Topology uncovered by DP and DPMCMC

(b) Topology uncovered by K2



(c) Manually designed topology

The subsequent step is to learn the network parameters (conditional probabilities). The internal parameters of the nodes were approximated through MAP estimation using *BDeu* priors initialized with a weight of 10 percent of the whole data set, which amounts to 7.5 pretended observations for each unseen event. Finally, as it is often the case with BNs, there is no ground truth on which to evaluate the inference capabilities of any learned network. Yet, it is possible to judge the relative performances of different network topologies using cross validation. In our particular case, we are interested in how good the predicted stability matches the observed stability for any of the computed networks. Note that it would be possible to infer the probability distribution over action features from known object features and stability outcomes as well as any other combination of random variables (RVs). However, as prediction capabilities of the networks form the basis for the later computation of affordances, we are going to limit ourselves to the evaluation of the stability inference problem. To do this, leave one out cross validation was used. The parameters of the three graph topologies shown in the previous figure were trained on the data from all experimental trials except those trials involving the object used for eventual inference evaluation. Then, each network was queried for a probability distribution Q over stability outcomes for each object/action pairing. From the data spared from parameter estimation, the MLE estimate of the distribution over stability outcomes P was computed. After that, the two distributions P and Q were compared using the KL divergence.

In short, statistical tests show ($p<0.01$) that the three methods perform differently. DPBN has the higher predictive power (for grasp stability), the manually designed networks lays somewhere in between and the K2 method is the worst.

In a final experiment – now that the BNs performance has been assessed – we tried to formalize affordances as the "best" match between object and action. The goal is to arrive at a scoring function measuring the match between each action and object, i.e. the affordance of the object formalized as *P(a|o)*. As mentioned earlier this probabilistic formalization is not only important in its own right, but also integrates into models of the mirror neuron system (Metta et al.). It is to be noted that both the distribution over the possible actions can be computed (though expensive) but also (more simply) only the maximum of such distribution.

As mentioned earlier, this model of affordances is well suited to be integrated in a model of mirror neurons (action recognition) for the iCub where affordances act as priors in a Bayes classification problem. This work can further be integrated (although this is left as a future extension) with the method developed by IST for estimating grasp points on objects.

UNIFE

UNIFE was involved in the exploration of the multi-modal representation of both the action itself and the object involved in the action. In particular on how learning of object affordances, object properties and physical laws can be acquired by interacting with objects in the world and incorporating invariant cause-effect relationships.

Task 4.2 Investigation of the cortico-spinal excitability during execution, observation and inhibition of object interception.

Results do not support the hypothesis that the motor system involvement during action observation is functionally equivalent to motor preparation, suggesting that motor representation activation is present in the observer only during the perception of the actual execution of another individual's action. This work has been submitted to European Journal of Neuroscience.

Patrice Senot, Laila Craighero, Giovanni Ottoboni, Chiara Zingales, Charalambos Papaxanthis, Luciano Fadiga. *Corticospinal excitability during motor preparation: a comparison among execution, voluntary inhibition, and observation of an interceptive task.* Submitted to European Journal of Neuroscience.

Task 4.2: Early affordant behaviours. Initial experiments will focus on self-exploration, to understand the development of the "basic" repertoire upon which an imitation system can develop. Successively the recognition of other individuals' actions will provide examples for acquiring new affordances.

Interception in humans is a complex visuo-motor task that requires in few hundreds of milliseconds to detect and process visual motion information, to estimate future position of object in space and time, to transform visual information into an appropriate motor action and to trigger this action in advance to compensate for physiological and mechanical delays. Despite this complexity, humans demonstrate rather good performance in interceptive actions. To investigate this ability and understand the characteristics of the underlying visuo-motor transformation, we estimated individuals' corticospinal facilitation by means of TMS at different time intervals during the phase immediately preceding an interceptive task of a falling object, in three different experimental conditions: when participants were required to catch a falling object, when they were asked to observe an agent catching it, and when they had to voluntarily refrain from catching it.

Figure 36: Experimental set-up. A tube was sliding along a vertical staff, passing between the participants thumb and fingers. The participants had to intercept (Execution condition) the bar, to observe a real actor intercepting the bar (Observation condition) or just looking at the falling of the tube (No-go condition).

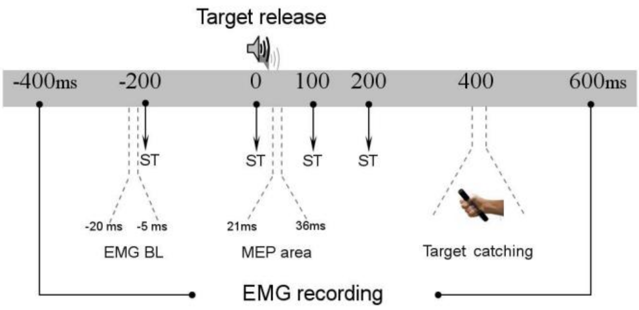


Figure 37: Schematic representation of the time course of experimental events. Arrows indicate the four stimulation times (ST) during Observation, Execution and No-go conditions. The baseline (BL) of the EMG activity was calculated before each ST and the area of the Motor Evoked Potential (MEP) after each ST. They are presented only once on the figures for clarity.

Results indicate that the involvement of the motor system during the preparatory phase of an interceptive task differs according to the tested experimental conditions. In particular, the execution and the voluntary inhibition of this action determine a completely different modulation of the motor system. During Execution condition corticospinal activity is almost always increased with respect to the baseline, a part from the period immediately after target releasing. This decreasing in excitability is considered, on the basis of previous studies, an indication of the readiness to react. During No-go condition corticospinal activity doesn't differ from baseline a part from a significant inhibition at the time approximately corresponding to the mean EMG onset during actual execution, indicating that participants were effortfully paying attention to the falling target. Finally, the mere observation of an agent preparing to execute an interceptive task, when the exact instant of action execution is perfectly known by the observer, is not sufficient to elicit a corticospinal modulation. Consequently, present results do not support the hypothesis that the motor system involvement during action observation is functionally equivalent to motor preparation, furthermore, they suggest that motor representation activation is present in the observer only during the perception of the actual execution of another individual's action.

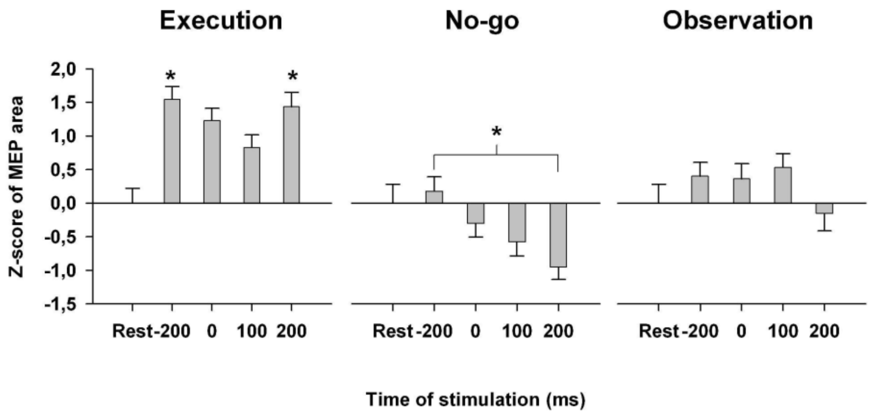
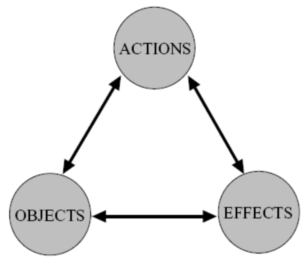


Figure 38: Time course relative to bar release (t = 0 ms) of Z-score of averaged FDI MEP area during execution (left), inhibition (middle) and observation (right) of target interception. Vertical bars represent standard error. Isolated asterisks denote statistically significant difference ($p < 0.05$) relative to respective baseline.

IST

In this Workpackage, IST continued the development of a general methodology to acquire affordances in an unsupervised manner. The approach assumes the existence of a set of elementary actions (sensorimotor coordination in WP3) that allow the robot to explore the environment and understand the interplay between actions, objects and action outcomes.



inputs	outputs	function
(O, A)	E	Predict Effect
(O, E)	A	Recognize action & Planning
(A, E)	O	Object recognition & selection

Figure 39: Affordances as relations between (A)ctions, (O)bjects and (E)ffects.

We use a Bayesian network to model the relation between actions, object properties and effects. In such a probabilistic framework, many of the quantities of interest are a function of the marginal probabilities of the Bayesian network. The model can be used for prediction, action selection or object selection. In addition to this, the use of Bayesian networks provides a generic and sound model that allows addressing learning and inference within the same framework. Furthermore, it is possible to model different learning contexts such as self-exploration, imitation or reinforcement learning.

The learned model is then used to predict the effects of actions, recognize actions performed by a human and to play simple imitation games. These imitation games are driven by the observed effects of the human action, and exploit knowledge contained in the affordance network to obtain the same effects (emulation). In this sense, imitation is not limited to mimicking the detailed human actions. Rather, it is used in a goal directed manner, as the robot may choose a very different action (when compared to that of the demonstrator) provided that its experience indicates that the desired effect can be met.

The main bulk of work developed so far in this Workpackage has been published as:

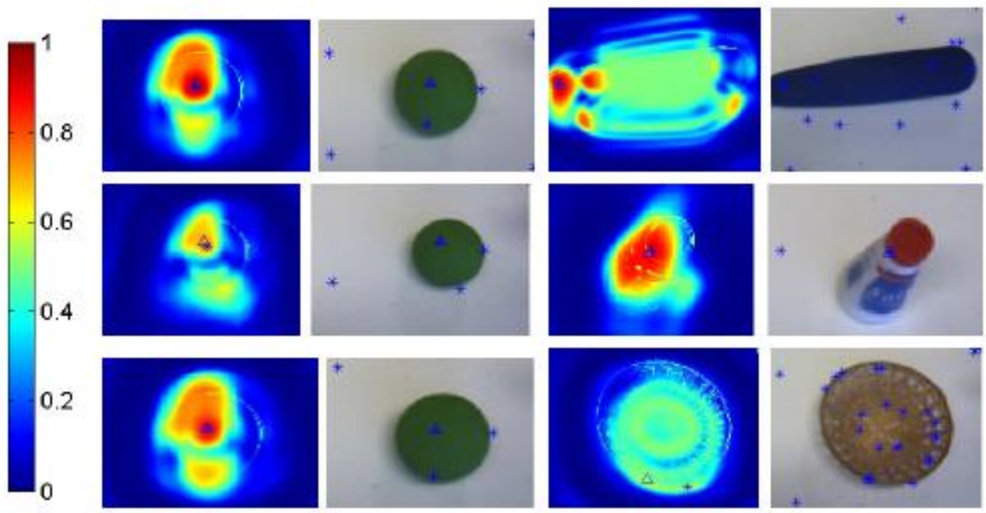
Luis Montesano, Manuel Lopes, Alexandre Bernardino, and José Santos-Victor, "Learning Object Affordances: From Sensory Motor Maps to Imitation, "IEEE Transactions on Robotics, vol. 24(1), February 2008.

and revised in:

A Computational Model of Object Affordances. L. Montesano, M. Lopes, F. Melo, A. Bernardino and J. Santos-Victor. Advances in Cognitive Systems, IET Publishers, 2009.

During the fifth year of the project we have completed the work on: (i) methods for learning grasping points from experiments, (ii) adding speech information to the affordance model and (iii) the software integration on the iCub, with a special emphasis on interaction with the reaching modules now available in the repository. We next briefly describe the work done on each direction.

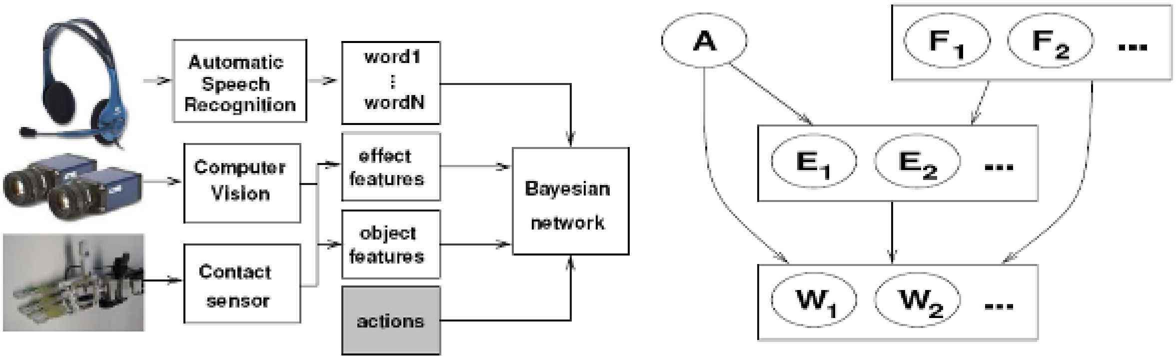
Learning visual descriptions of grasping points from experience – Determining where and how to grasp an object is the first step towards fine manipulation. Actually, an object affords certain types of grasping and not others. For instance, grasp and grip actions will select different grasping points for the same objects. We are currently developing non parametric learning algorithms to estimate the probability of success of different grasps according to the visual input features. The procedure is the following. The examples are based on the robot's own experience on different objects. Based on this example, we compute a map between visual features and the probability of grasps using kernel based smoothed beta distributions. The picture below illustrates the prediction of grasping probability for novel objects.



The proposed method computes a posterior distribution for each point in the image. This means that, in addition to the probability of being a good grasping point, we have the certainty of the robot about this prediction. This information has been used to actively look for good grasping points in novel objects by reusing the experience of previous objects to direct the exploration. As a result, the number of trials before the robot discovers a graspable point is much lower than on a random approach that ignores previous experience and the corresponding confidence.

Learning grasping affordances from local visual descriptors. Luis Montesano and Manuel Lopes. IEEE - International Conference on Development and Learning, Shanghai, China, 2009.

During this year we have finished the work on labelling the affordance knowledge using verbal descriptions of a human. This has been done by extending the network to include nodes to represent the labels. These nodes can depend only on the affordance nodes. This simple model captures co-occurrences between the network configurations and the different labels and exploits them to link them together.



Affordance Based Word-To-Meaning Association, V. Krunic, G. Salvi, A. Bernardino, L. Montesano, J. Santos-Victor. International Conference on Robotics and Automation 2009, Kobe, Japan.

The demo shown during the Y4 review has been now completely rebuilt to comply with the cognitive architecture and to integrate the developments done during the last year. In particular, we have integrated new perception capabilities for the detection and segmentation of the objects and the reaching module that allows the robot to move the hand to a workspace position where the object is located.

The software necessary to conduct this demo, was redesigned and integrated in the iCub software architecture. A complete description of the modules is provided in the wiki documentation (http://eris.liralab.it/wiki/DemoAff).

Deviations from the project work-programme

None.

List of deliverables

Del. no.	Deliverable name	Workpackage no.	Date due	Actual/Forecast delivery date	Lead contractor
D4.1	Results of experiments on affordant behaviours.	4	M65	M65	IST
D4.2	Software for the iCub & integration in the iCub Cognitive Architecture.	4	M65	M65	IST and UGDIST

List of milestones

Milest one. no.	Milestone name	Workpackage no.	Date due	Actual/Forecast delivery date	Lead contractor
M4.3	Release of version 2.0 of the iCub software	4	M65	M65	UGDIST

WP5N – Imitation and Communication

Workpackage objectives

This new WP has been created in response to suggestions by project reviewers to merge the closely related WP5 on imitation and WP6 on gesture communication. The main emphasis during the final phase of Robotcub (fifth period) will be on a) the integration of previous results on the iCub platform, b) to use a common developmental framework (the IHA Interaction History Architecture previously developed in WP6) as a basis for the integration of gesture communication interaction games (previously WP6) to be demonstrated on the iCub, and c) to investigate the integration of skill acquisition through imitation (previously WP5).

This WP investigates the regulation of interaction dynamics of social interaction during human-robot play and its development in ontogeny. The pre-requisites for interactive and communicative behaviour grounded in sensorimotor experience and interaction histories will be investigated and developed with specific consideration of interaction kinesics (including gestures, synchronization and rhythms of movements etc.). Social drives for interaction, imitation and communication will be exploited to make use of non-verbal social cues in ontogeny in the course of human-robot interaction.

Active tasks

Task 5N.1: Investigation of the effect of physical presence on human-human gesture interaction games.
Task 5N.2: Investigation of using cues in the regulation of human-humanoid interaction games.
Task 5N.3: Implementation of gesture communication interaction games integrated with IHA architecture demonstrable on a humanoid robot, release in the iCub software repository and demo on the iCub.
Task 5N.4: Human-robot imitative learning release in the iCub software repository and demo on the iCub.

Progress towards objectives

This Workpackage merges the previous WP5 and WP6 to address the goal of integrating Imitation and Communication and other work in an ontogenetic framework on the iCub platform. Imitation plays a central role and communication is strongly related to imitation as regards social cues, turn-taking, and communicative functions. The activities in this Workpackage addresses the cognitive skills required for imitative behaviours and the cognitive skills required for communicating through body gestures.

These cognitive skills include:

- the ability to recognize and interpret somebody else’s gestures in terms of its own capabilities (mirror effects);
- the ability to learn new gestures on the basis of the observation of those in other individuals;
- the ability to recognize the purpose of other people’s gestures, such as the goal of manipulating objects in a certain specific way;
- the ability to predict the result of a demonstrated manipulation task and to use this ability to discriminate between good and poor demonstrations of manipulation tasks based on their affordances;
- finally, the ability to decide what part of the demonstration is relevant to imitation.

Prerequisites to these skills are the skilful control of arms and body in order to produce communicative gestures reflecting communicative timing or turn-taking, tracking and recognizing someone else's gestural timing, synchrony, and social engagement, to generalize and acquire simple communicative behaviours making use of social cues, to respond adequately to timing and gesturing of an interaction partner, and to harness turn taking as the underlying rhythm of gestured communication. That is, both the "static" aspect of recognition of actions and their social & temporal qualities have to be mastered before proper imitation and communication can happen.

Progress was made toward the objectives of WP5N along the lines delineated above. More specifically, work was conducted from both a robotics perspective (EPFL, UNIHER, IST) and from a biological perspective via human studies (UNIFE, UNIUP, UNIHER, EPFL).

A large part of the robotics work at UNIHER took a human-robot interaction perspective to analyzing and developing controllers to enhance human-robot communication. This work addressed the above delineated goals of determining the role that timing, social cues and gesture recognition play in Human-Robot communication. Further, progresses on the development of algorithms for imitation learning were made, by extending EPFL's work on statistical estimate of motion dynamics to allow robust estimation of arbitrary non-linear autonomous dynamical systems. In addition, both EPFL and UNIHER devoted important person/month to release software and prepare the demonstrators (documented in deliverables DN5.2-3).

UNIFE conducted a number of human studies on various topics pertaining to the basis of human-human communication and imitation. These studies focused on the observation-action/perception-action loop for both basic motor task and high-level cognitive tasks, such as speech production and perception. In addition, in collaboration with EPFL, UNIFE conducted a user-study to delineate the variables controlled during imitation of simple goal-directed arm reaching motion. This study informed the development of a computational model of reaching movement at EPFL that uses the same non-linear dynamical form as that used in the robotics imitation work mentioned above. The main theme of UNIFE experiments is in determining the role of Broca's area in the perception of various types of events (biological vs. non-biological) but also on the involvement of the motor system in the perception of speech and in inter-personal interaction under the influence of a reward.

IST has contributed to the goals of WP5N by modelling social learning (together with UNIUP), by developing methods for inverse reinforcement learning whereby the mechanisms underlying a demonstrated tasks are modelled, and by learning language related affordances with a Bayesian Network formalism analogous to the methods developed in WP4.

Deliverable D5N.1 provides a high-level summary of each of these studies including links to related publications. All associated publications are provided as PDF files in the attachments. All the work that relates to design of robot controllers for the iCub is available on the SVN repository.

The work on developing software for imitation and communication in a humanoid robot conducted within WP5N will be show-cased through two demonstrators by UNIHER and EPFL that form deliverable D5N.3

UNIFE

UNIFE contribution to the WP5N was mainly based in the investigation of the pre-requisites for interactive and communicative behaviour grounded in sensorimotor experience. To this purpose different aspects of interaction, imitation and communication have been investigated.

Task 5N.1: Investigation of the effect of physical presence on human-human gesture interaction games.

(a) Broca's area has been considered, for over a century, as the brain centre responsible for speech production. Modern neuroimaging and neuropsychological evidence have suggested that a wider functional role is played by this area. In addition to the evidence that it is involved in syntactical analysis, mathematical calculation and music processing, it has recently been shown that Broca's area may play some role in language comprehension and, more generally, in understanding actions of other individuals. As shown by functional magnetic resonance imaging, Broca's area is one of the cortical areas activated by hand/mouth action observation and it has been proposed that it may form a crucial node of a human mirror-neuron system. If, on the one hand, neuroimaging studies use a correlational approach which cannot offer a final proof for such claims, available neuropsychological data fail to offer a conclusive demonstration for two main reasons: (i) they use tasks taxing both language and action systems; and (ii) they rarely consider the possibility that Broca's aphasics may also be affected by some form of apraxia. We administered a novel action comprehension test — with almost no linguistic requirements — on selected frontal aphasic patients lacking apraxic symptoms. Patients, as well as matched controls, were shown short movies of human actions or of physical events. Their task consisted of ordering, in a temporal sequence, four pictures taken from each movie and randomly presented on the computer screen.

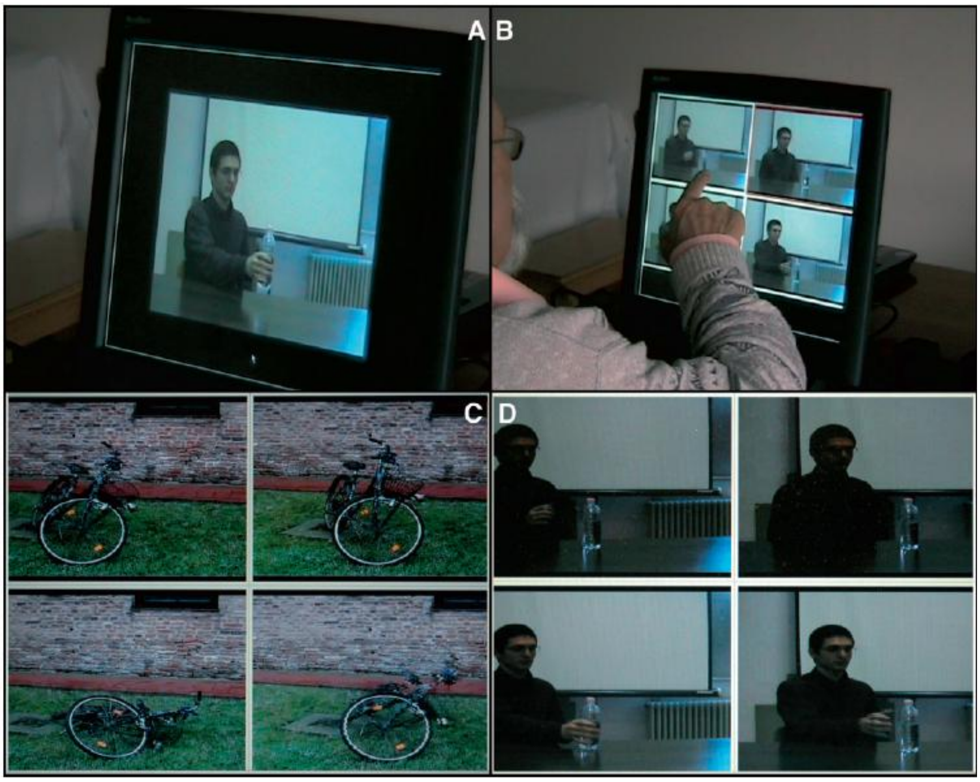


Figure 40: Experimental setup and task (A) The videoclip is presented on the screen, (B) Four snapshots are presented at the four corners of the screen, (C) Exampleof physical events snapshots and (D) Example of Human Action snapshots.

Patient’s performance showed a specific dissociation in their ability to re-order pictures of human actions (impaired) with respect to physical events (spared).

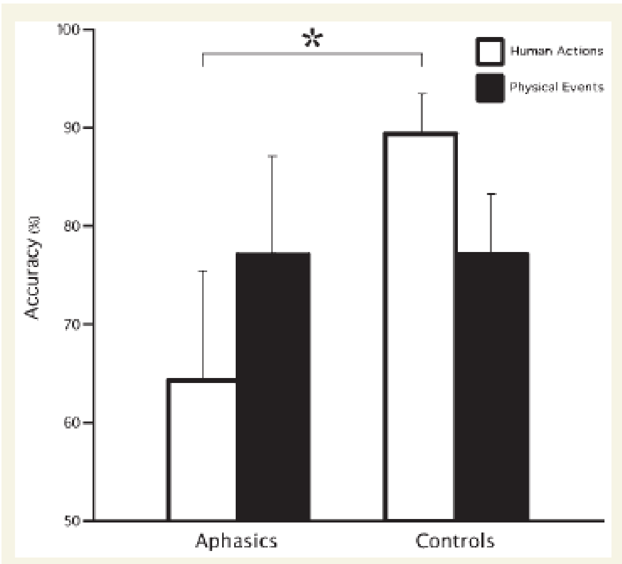


Figure 41: Accuracy results: Histograms depict the accuracy ratio in aphasic patients and normal subjects (Controls) for both human actions (white bars) and physical events (black bars) conditions. Error bars are shown (mean and standard deviation). Asterisks denote statistically significant differences (p<0.05) in accuracy ration between aphasics and controls in the human action condition.

The present work shows that frontal aphasic patients, characterized by a lesion centred in the left pars opercularis of Broca's region and by the absence of apraxic symptoms, are specifically impaired in sequencing pictures representing actions (transitive or intransitive) performed by a human agent but not in sequencing physical events.

Why are these patients not able to solve the sequencing task for human actions only? In our experiment, subjects were requested to understand what they were observing in the video clip, and then order single snapshots into a meaningful sequence. To do this, we suppose the subjects had to represent (and replay) the rules connecting critical information presented in the videos. The interpretation we favour is that, to correctly sequence human actions, subjects were implicitly mapping the observed actions onto their own motor repertoire. In other words, the subjects had to gain access to 'how' a given action was composed in terms of simple units, and harmoniously (and pragmatically) restructure it through an embodiment process. Conversely, in the case of physical events, such an implicit and embodied motor representation was unnecessary to solve the task.

Why should this capacity of representing action pragmatics be encoded in Broca's area? In our view, Broca's area might have specialized in encoding complex hierarchical structures of goal-directed actions, and to eventually apply these pragmatic rules to more abstract domains. Therefore, the language-related functions sub-served by Broca's region could be the most eloquent part of a more general computational mechanism shared by multiple domains. Such mechanisms could be imagined as a poly-modal syntax endowed with the ability to organize and comprehend hierarchically dependent elements into meaningful verbal and non-verbal structures.

(b) We previously demonstrated that patients with a lesion involving Broca's area present deficits in reordering pictures showing human actions, whereas this ability was preserved for non-biological events. This finding further supports the hypothesis that Broca's area could play a key role in encoding the hierarchical structure or, in other words, the motor syntax, of human actions. However, although patient studies provide useful cues about the causal relationship between the Broca's area lesion and the aforementioned behavioural deficits, the conclusions of such a study may be biased by the extent of the lesion and/or the possible brain reorganization, which may have occurred since that lesion. To circumvent these limitations, we performed an interferential transcranial magnetic stimulation (TMS) experiment in healthy individuals, based on a paradigm similar to that we previously developed. TMS was delivered over the pars opercularis of left Brodmann area (BA) 44, which corresponds to the posterior part of Broca's region.

The task consisted in reordering three pictures extracted from a video showing either a human action or a non-biological event that is an object in movement.

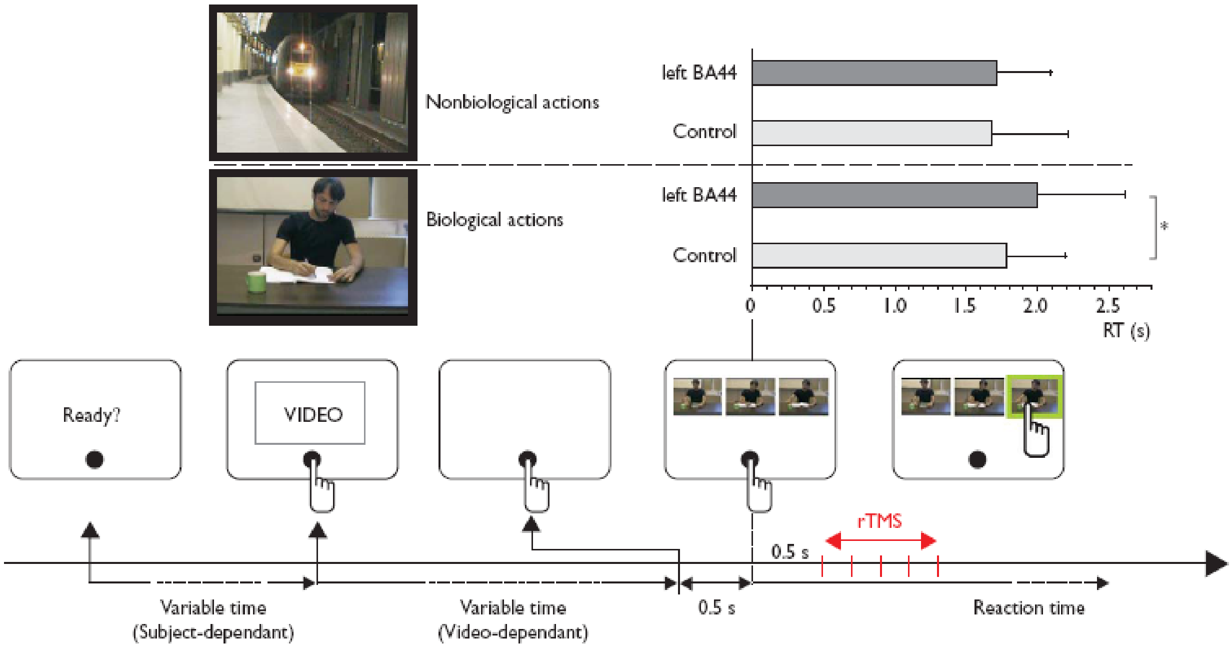


Figure 42: Experimental procedure and effect of left BA44 virtual lesions on reaction times. Bottom: time course of a trial. Each trail started with the display of a message ("ready?") that instructed the participant to put his/her right index finger on the circle displayed at the bottom of the touch screen, a position he/she had to keep until the display of the three pictures (see below). This contact of the index finger with the touch screen triggered the display of a short video clip (duration 1-48s) showing either a biological action or a nonbiologial sequence. At the end of the video, a blank screen appeared for 500ms, followed by three pictures extracted from the video clip. The participant had to point toward, and touch, the picture showing the middle of the biological action or of the nonbiological sequence. When the answer was correct, the selected picture was surrounded by a green frame; in case of an incorrect response, the frame was red. The next trial started after a 1s delay. Repetitive transcranial magnetic stimulation (rTMS) (5Hz, five pulses, shown in red) was delivered 500ms after the display of the three pictures either over the left BA44 or over the leg representation of the primary somatosensory cortex (control). Upper right corner: histograms showing the mean reaction times (RT) and standard deviations (SD) in different conditions across participants (n=13) for biological and nonbiological sequences. * significant results (p<0.05).

rTMS (110% of resting motor threshold of the first dorsal interosseus muscle, 5 Hz, five pulses) was delivered 500 ms after the display of the three pictures over left BA44 and, as a control site, over the leg representation.

Results showed that a virtual lesion of left BA44 affected only the reordering task for transitive and syntactic biological actions, that is, actions showing both a hand–object interaction and a complex sequencing of individual motor acts. Nontransitive and nonsyntactic actions and nonbiological sequences remained unaffected by left BA44 virtual lesions. This study further strengthens the view that the involvement of Broca's area in language, and particularly in syntax processing, might be rooted in its premotor origin, as shown by the finding that actual or virtual lesions of this area led to deficits in pragmatic encoding of observed actions.

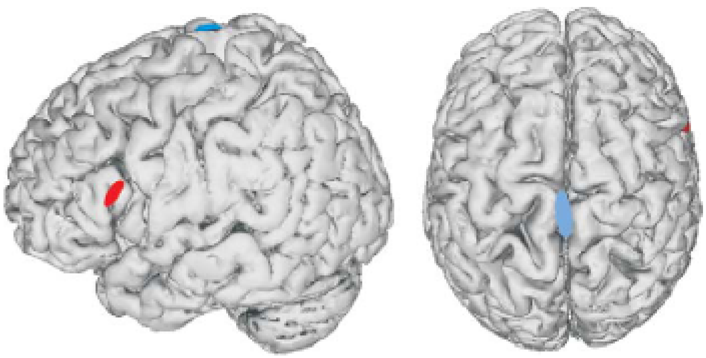


Figure 43: Mean location of stimulation sites. The two stimulation sites were the pars opercularis of the inferior frontal gyrus (left BA44, red eclipse) and, as a control site, the part of the primary somatosensory cortex located near the midline, corresponding to the representation of the lower limb (S1 leg, blue eclipse). Each eclipse is centred on the mean Montreal Neurological Institute gathered for all participants. The average of the coordinates (mean±SD of x,y, and z) for left BA44 were -59.1±2.6, 16.4±3.8, 20.6±4.7mm, and -2.7±2.4, -20.5±8.5, 79.4±5.9mm for S1 leg. The surface of the eclipse represents the 95% confidence interval of the normalized coordinates calculated for each participant.

(c) Social and economic literature generally considers that the relevance of property rights in human interaction arises from explicit cognitive processes, which emerge with social competence. The main focus of our experiment was to verify whether the formal entitlements of property rights, regardless of any legitimating activity undertaken by participants, play a significant role within a context where interaction between individuals does not involve any explicit process related to emotional cues and/or to strategic or "perspective-taking" considerations. Furthermore, we wanted to investigate if the allocation of property rights automatically influence individual's behaviour at a very low level, such as the intensity of muscle involvement during the execution of hand actions.

To this purpose, twelve pairs of participants, prevented from any visual or verbal exchange, were submitted to a simple motor coordination task. Each couple had to cooperatively hold a small sphere between their right index fingers and to drop it alternately into one of two containers placed below their hands, while electromyography of the right first dorsal interosseus (FDI) muscle of each participant was recorded.

Each successful trial was differently rewarded with a given amount of money according to the experimental condition, and the rewarding rules were communicated before starting each session. Consequently, for the same action (e.g., pushing the ball into the leftside container) each participant could receive a reward in one session but not in another. The total monetary reward gained by each subject in each condition was always the same. Finally, we correlated muscle involvement to the scores obtained in a social attitude questionnaire to verify if the degree of prosocial propensity covertly modulates motor behaviour. We split the sample of subjects into high-prosocial and low-prosocial individuals.

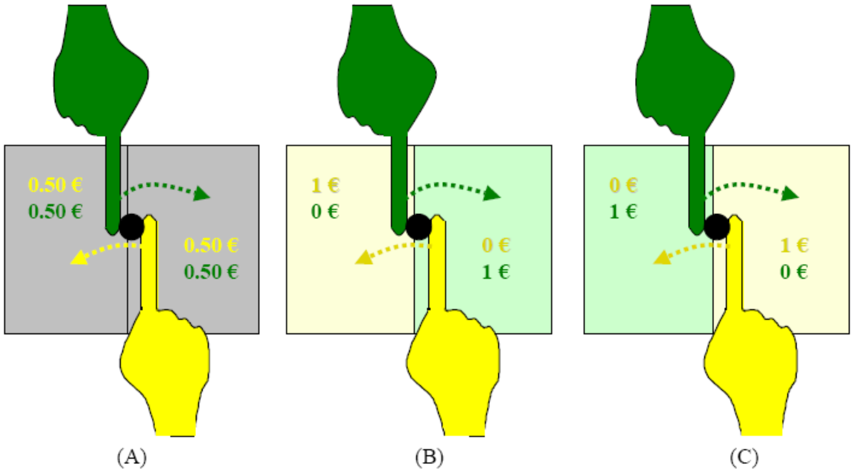


Figure 44: Schematic view of the experimental apparatus used in the three experimental conditions. Subjects' hands laid on a Plexiglas plate with the two index fingers positioned in correspondence of a square hole (the rectangle shown in the figure). Under the Plexiglas plate, at a distance of 10cm from it, there were two containers (the two grey areas shown in panel A) where the subjects had to drop the sphere held by their index fingers according to the specific instructions provided for each experimental conditions. The moment at which the sphere touched the floor of the container was detected by a load cell. The monetary incentives associated to the three experimental conditions were the following: Condition 1 (A): each subject (Yellow and Green) get Euro 0.50 at any trial. Condition 2: the Yellow (Green) subject is coupled with the Yellow (Green) container; the pushing subject gets Euro 1 while the pulling one gets zero. Condition 3: the contained were reversed: the pushing subject gets zero and the pulling one gets 1 Euro. Ten trials for each condition. Each subject received 15 Euros.

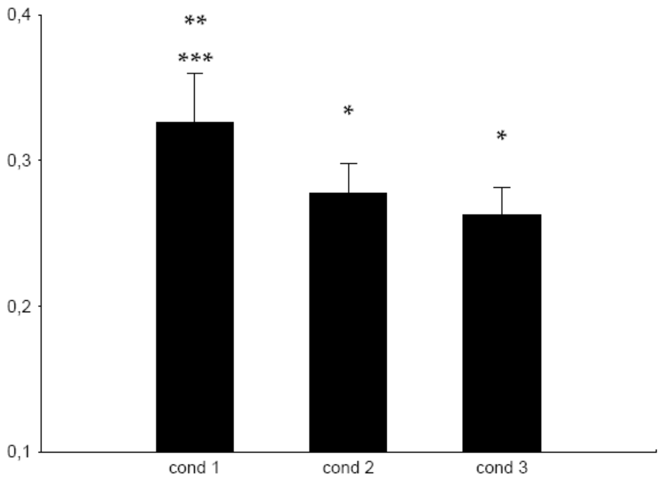


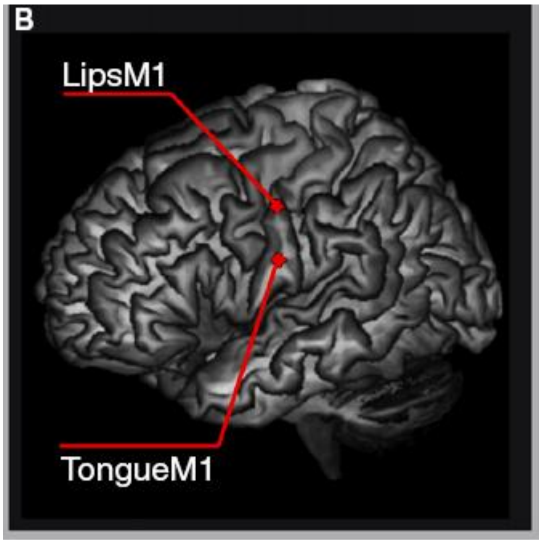
Figure 45: Mean values of EMG signals recorded from the FDI muscle for all subjects in the three experimental conditions, when pushing the sphere into the target container placed at her left side. Error bars show the standard error and mean. Ordinates: z-score of EMG signals. Asterisks indicate the presence of a significant difference between conditions (*, difference from Condition 1; **, *, difference from Condition 2 and 3, respectively).**

Subjects were able to coordinate almost perfectly across conditions 1, 2 and 3. Thus, from a distributional point of view it does not emerge any difference in behaviour associated with the different incentive

protocols. However, substantial differences arose from EMG data processing, revealing not only that muscle involvement in executing the same motor act is affected by the allocation of formal property rights, but also that the modulation of the effort is correlated with the degree of prosocial propensity of subjects. With respect to the two groups of individuals our main result was that high-prosocial subjects performed the task without any significant difference among conditions, while low-prosocial subjects exerted a significant lower effort in Condition 3 than in Condition 1.
Therefore, our results suggest that even when the outcome of the play indicates perfect cooperation, electrophysiological measurements may reveal differences in attitudes and beliefs that guide social interaction.

(d) Listening to speech recruits a network of fronto-temporoparietal cortical areas. Classical models consider anterior (motor) sites to be involved in speech production whereas posterior sites are considered to be involved in comprehension. This functional segregation is challenged by action perception theories suggesting that brain circuits for speech articulation and speech perception are functionally dependent. Although recent data show that speech listening elicits motor activities analogous to production, it's still debated whether motor circuits play a causal contribution to the perception of speech.

Here, we set out to investigate the functional contributions of the motor-articulatory systems to specific speech-perception processes. To this end, a cross-over design orthogonalizing the effect of brain-phonology concordance with those of linguistic stimuli and TMS loci was chosen. Phonemes produced with different articulators (lip-related: [b] and [p]; tongue-related: [d] and [t]) were presented in a phoneme discrimination task. The effect of TMS to lip and tongue representations in precentral cortex, as previously described by fMRI, was investigated. Double TMS pulses were applied just prior to stimuli presentation to selectively prime the cortical activity specifically in the lip (LipsM1) or tongue (TongueM1) area. Behavioural effects were measured via reaction times (RTs) and error rates.



RT performance showed a behavioural double dissociation between stimulation site and stimulus categories. RT change of phonological decisions induced by TMS pulses to either the TongueM1 or LipM1 showed opposite effects for tongue- and lip-produced sounds. Therefore, the stimulation of a given

M1 representation led to better performance in recognizing speech sounds produced with the concordant effector compared with discordant sounds produced with a different effector. These results provide strong support for a specific functional role of motor cortex in the perception of speech sounds. In parallel, we tested whether TMS was able to modulate the direction of errors. Errors were grouped in two classes: lip-phoneme errors (L-Ph-miss) and tongue-phoneme errors (T-Ph-miss).

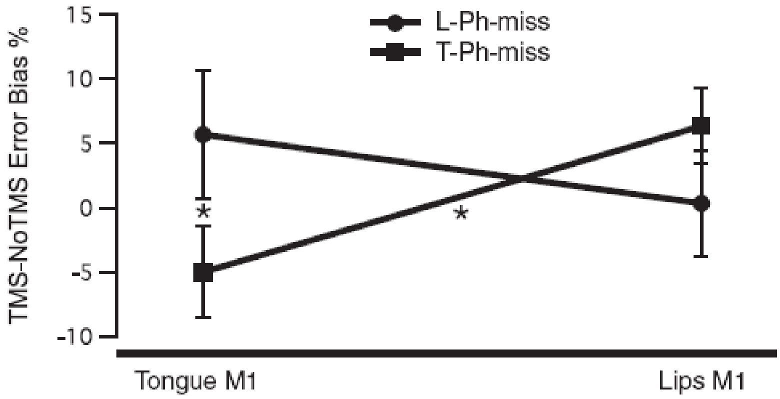


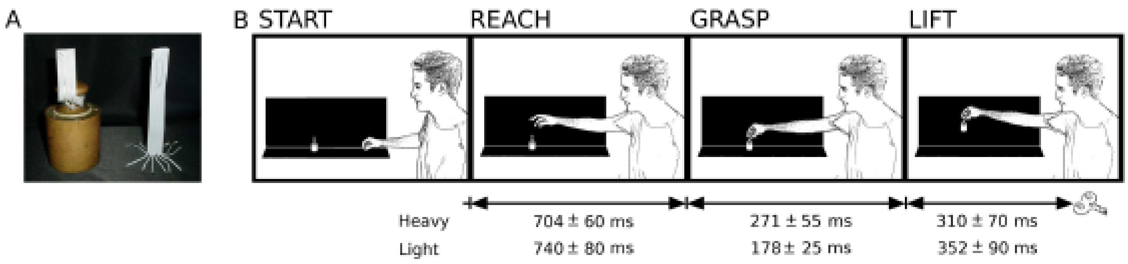
Figure 46: Accuracy results. We tested whether TMS was able to modulate the direction of errors, i.e. if the stimulation of the TongueM1 increases the number of labial sounds erroneously classified as dental and vice versa. After TMS, dissociation between stimulation site (TongueM1 and LipM1) and the type of error (L-Ph-miss, T-Ph-miss) was found. The ordinates represent the amount of error change induced by the TMS stimulation.

The double dissociation we found in the present work provides evidence that motor cortex contributes specifically to speech perception. As shown by both RTs and errors, the perception of a given speech sound was facilitated by magnetically stimulating the motor representation controlling the articulator producing that sound, just before the auditory presentation.

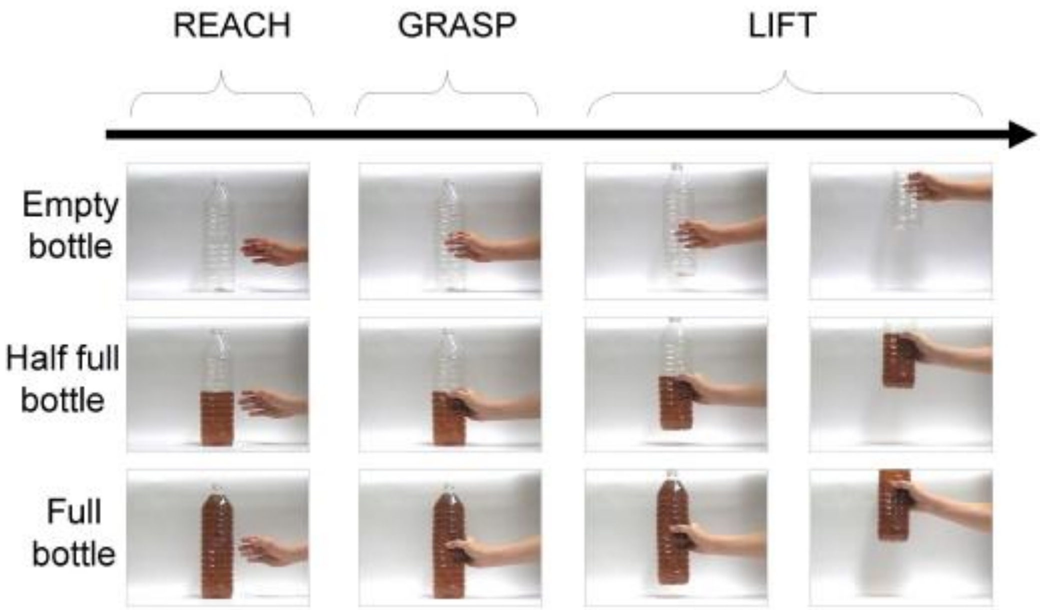
Biologically grounded models of speech and language have previously postulated a functional link between motor and perceptual representations of speech sounds. We demonstrate here for the first time a specific causal link for features of speech sounds. The relevant areas in motor cortex seem to be also relevant for controlling the tongue and lips, respectively.

(e) Several transcranial magnetic stimulation (TMS) studies report that viewing other's actions facilitates the neural representation site of the onlooker's muscles that are recruited during the actual execution of the observed action. With the present study, we investigated whether this muscle-specific facilitation of the observer's motor system reflects the degree of muscular force that is exerted in an observed action.

Two separate TMS-experiments were performed in which corticomotor excitability was measured in the hand area of the primary motor cortex (M1) while subjects observed the lifting of objects with different weights. The type of action 'grasping and lifting the object' was always identical but the grip force varied according to the object's weight.

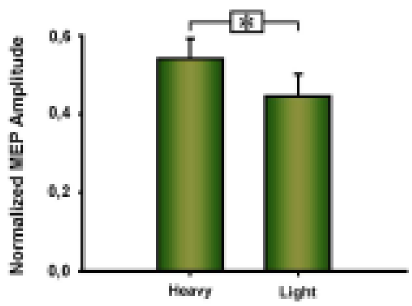


Experiment 1

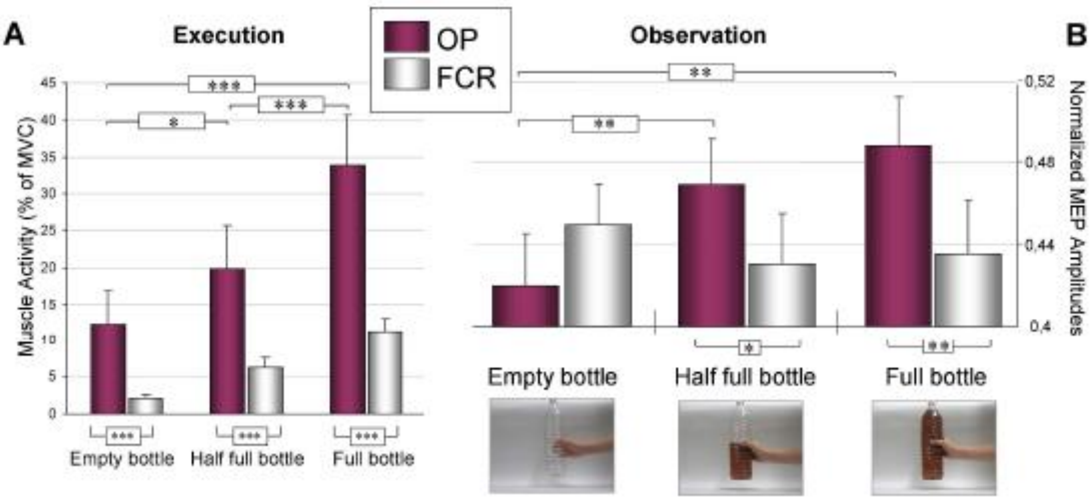


Experiment 2

Results indicated that, in accordance to previous findings, corticomotor modulation during action observation is specific for those muscles involved in the execution of the observed action, and that this muscle specific modulation is influenced by the force requirements of the observed actions, such that higher corticomotor excitability was found for the heavy object conditions than for the light object conditions.



Experiment 1



Experiment 2

In summary, the present study provides some exciting new evidence that resonant activity in motor areas is highly specified to map different features of observed actions. More specifically, data convincingly indicated that observation-induced facilitation of the observer's primary motor cortex reflects the muscular requirements of the observed movement, not only in terms of the muscle used in the observed motion, but also in terms of the force that is produced in the particular muscle.

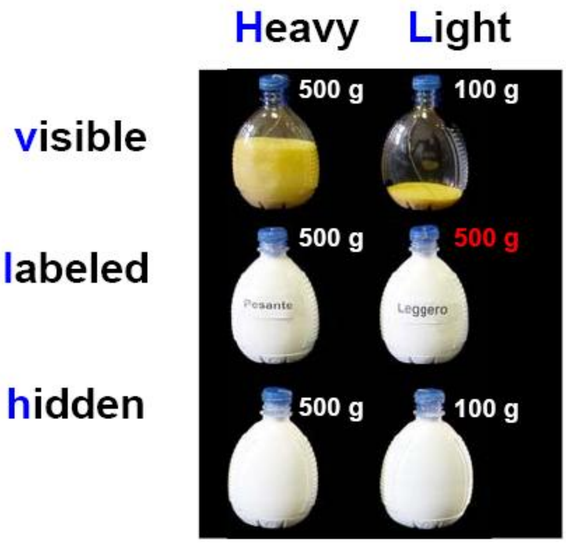
(f) It is assumed that action observation elicits the motor representation that is evoked during execution of the same action on the basis of data indicating the sharing of muscle specificity and temporal pattern during both observation and execution tasks. We have collected indication that force required to execute the action is also coded during observation. What information is used by the observers to code force? It has been proposed that kinematics cues could be used to estimate the weight of an object during observation of its lifting. However it is not known if this information is sufficient or if it requires visual cues and if it can be modulated by explicit cognitive cues.

Using single pulse Transcranial Magnetic Stimulation (TMS), we tested the following questions:

1. Is motor cortex facilitation during action observation modulated by the amount of force required to accomplish the action even when no explicit visual weight-related cues are present?
2. Is this modulation influenced by explicit cognitive information?

Motor Evoked Potentials (MEP) elicited by TMS stimulation of M1 representation of First Dorsal Interosseous (FDI) muscle were measured during the observation of reach-grasp-lift actions upon 6 different objects:

1 transparent empty bottle (VisLight);
2 transparent full bottle (VisHeavy);
3 opaque empty bottle (HidLight);
4 opaque full bottle (HidHeavy);
5 opaque full bottle labelled light (LabLight);
6 opaque full bottle labelled heavy (LabHeavy).

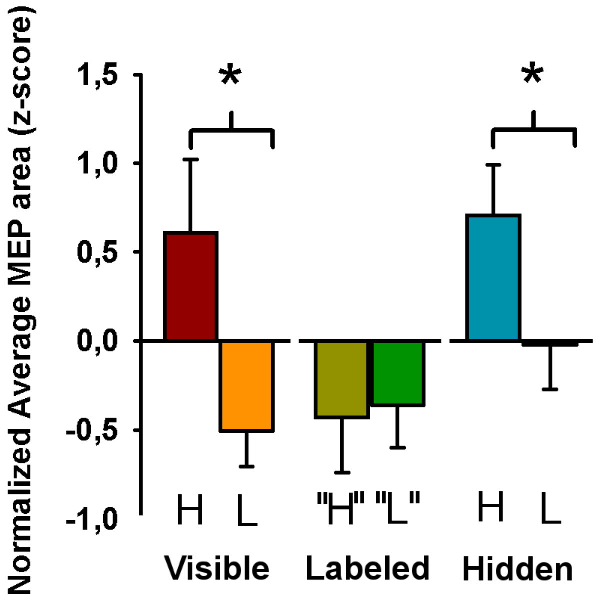


Initial position **Grasping phase** **Lifting Phase**

Light objects were 100g and heavy were 500g. This difference of weight induced clear different patterns of muscle contraction and kinematics. TMS was applied when this difference was found to be maximal, in a 100 ms window after the beginning of lifting. Condition 1 and 2 afforded full knowledge of weight differences and kinematics information, 3 and 4 only kinematics, 5 and 6 no kinematics but hi-level cues (labels).

Results showed that MEP amplitude was modulated by the force required to lift the object when weight - related cues are fully available (“visible” condition). This modulation was also present when only kinematic cues are available (“hidden” condition). Since all subjects reported the presence of only 5 objects (they recognized only one opaque object instead of two), the observed modulation in the “hidden” condition should result from an implicit processing of weight information. Therefore, our results show that the motor cortex does scale for the amount of muscle activity present in the observed action by analyzing movement kinematics.

The fact that force coding is abolished when incongruent (kinematic Vs cognitive) information are present (“labelled” condition) suggests that the presence of conflicting information could abolish the motor plan elicited by action observation.



UNIHER

The work at UNIHER on Imitation and Gesture Communication (WP5N) in the final project phase has continued our research in RobotCub along three key lines of investigation a) the study of gesture communication and imitation in user studies with child and adult participants, b) the development of a computational architecture for development and learning in human-humanoid interaction, and c) the in-depth analysis of human-robot interaction in a variety of interaction scenarios in order to illuminate aspects of timing, social cues, motor interference and well as possible benefits of such interaction in robot assisted play for children. All research activities have been completed successfully leading to a large number of journal and conference publications.

UNIHER carried out Tasks 5N.1, 5N.2, and 5N.3 contributing to the scientific report D5N.1 for WP5N, as well as software repository and demo contributions (D5N.2, DN.3) for the Imitation and Communication WP.

Task 5N.1: Investigation of the effect of physical presence on human-human gesture interaction games.

For this task, a study with human participants interacting with various degrees of physical presence was carried out. Results are reported in a journal paper, where we present an empirical study investigating the effect of embodiment and minimal gestures in an interactive drumming game consisting of an autonomous child-sized humanoid robot (KASPAR) playing with child participants. Each participant played three games with a humanoid robot that played a drum whilst simultaneously making (or not making) head gestures. The three games included the participant interacting with the real robot (physical embodiment condition), interacting with a hidden robot when only the sound of the robot is heard (disembodiment condition; note that the term ‘disembodiment’ is used in this paper specifically to refer to an experimental condition where a physical robot produces the sound cues, but is not visible to the participants), or interacting with a real-time image of the robot (virtual embodiment condition). We used a mixed design where repeated measures were used to evaluate embodiment effects and independent-groups measures were used to study the gestures effects. Data from the implementation of a human–

robot interaction experiment with 66 children are presented, and statistically analysed in terms of participants' subjective experiences and drumming performance of the human–robot pair. The subjective experiences showed significant differences for the different embodiment conditions when gestures were used in terms of enjoyment of the game, and perceived intelligence and appearance of the robot. The drumming performance also differed significantly within the embodiment conditions and the presence of gestures increased these differences significantly. The presence of a physical, embodied robot enabled more interaction, better drumming and turn-taking, as well as enjoyment of the interaction, especially when the robot used gestures. While the experiments in this study had to be conducted with KASPAR, the findings are also very relevant to future studies with the iCub in cases where different robot embodiments are used.

Hatice Kose-Bagci, Ester Ferrari, Kerstin Dautenhahn, Dag S. Syrdal, Chrystopher L. Nehaniv (2009), Effects of Embodiment and Gestures on Social Interaction in Drumming Games with a Humanoid Robot. Advanced Robotics, 23(14): 1951-1996, 2009.

Task 5N.2: Investigation of using cues in the regulation of human-humanoid interaction games.
This direction formed a major part of UNIHER's scientific work. Resulting in 9 publications (3 journal papers and 6 conference papers) in the final period of RobotCub, some of which represent the investigation into cues such as timing, gesture, body expression and communicative aspects of imitation (former Task 5.1, an update of D6.5). Some of these publications report the culmination or updates of previous work (such as with timing and robot-human drumming interactions; investigation into the adaptive regulation of robot behaviour in response to human-robot interaction), while others overview the issues and developments over the course of recent years (e.g. in methodology of human-humanoid studies, or design and deployment of the low-cost minimally expressive humanoid robot KASPAR specifically used for human-robot interaction experiments in RobotCub prior to the availability of the iCub to the UNIHER team). D5N.1 reports full details on these investigations into cues in interaction.

Hatice Kose-Bagci, Kerstin Dautenhahn, Dag S. Syrdal and Chrystopher L. Nehaniv (in press), Drum-mate: Interaction dynamics and gestures in human-humanoid drumming experiments. Connection Science.

Hatice Kose-Bagci, Frank Broz, Qiming Shen, Kerstin Dautenhahn, Chrystopher L. Nehaniv (2010), As Time Goes by: Representing and Reasoning Timing in the Human-Robot Interaction Studies, AAAI - Spring Symposium 2010: It's All in the Timing: Representing and Reasoning about Time in Interactive Behavior, Stanford University, Palo Alto, California, Extended abstract accepted for publication.

H. Kose-Bagci, Kerstin Dautenhahn, and Chrystopher L. Nehaniv (2009), Drumming with a Humanoid Robot: Lessons Learnt from Designing and Analysing Human-Robot Interaction Studies, Proc. AAAI - Spring Symposium 2009: Experimental Design for Real-World Systems, Stanford University, Palo Alto, California, March 22-25, 2009, AAAI Technical Report SS-09-03, AAAI Press, pp. 25-32.

Kerstin Dautenhahn, Chrystopher L. Nehaniv, Michael L. Walters, Ben Robins, Hatice Kose-Bagci, N. Assif Mirza, Michael Blow (in press) KASPAR – A Minimally Expressive Humanoid Robot for Human-

Robot Interaction Research. Special journal issue on "Humanoid Robots" for Applied Bionics and Biomechanics, published by Taylor and Francis.

Dorothée François, Kerstin Dautenhahn and Daniel Polani (2009) Using Real-Time Recognition of Human-Robot Interaction Styles for Creating Adaptive Robot Behaviour in Robot-Assisted Play. IEEE Symposium on Artificial Life 2009, ALIFE'09, Nashville USA, pp. 45 – 52. *Winner of Best Paper Award

Dorothée François, Stuart Powell and Kerstin Dautenhahn (2009). “A long-term study of children with autism playing with a robotic pet: Taking inspirations from non-directive play therapy to encourage children’s proactivity and initiative-taking”. Special journal issue on Robots in the Wild: Exploring human-robot interaction in naturalistic environments, Interaction Studies 10:3, pp. 324–373.

Dorothée François, Daniel Polani, Kerstin Dautenhahn (2009) Towards Socially Adaptive Robots: A Novel Method for Real Time Recognition of Human-Robot Interaction Styles. Procs 8th IEEE-RAS Int Conf on Humanoid Robots (Humanoids 2008), December 1-3, 2008, pp.353-359.

Qiming Shen, Hatice Kose-Bagci, Joe Saunders, Kerstin Dautenhahn (2009) An Experimental Investigation of Interference Effects in Human-Humanoid Interaction Games. IEEE RO-MAN 2009, 18th IEEE International Symposium on Robot and Human Interactive Communication Sep. 27 - Oct. 2, 2009, Toyama International Conference Center, Japan.

Qiming Shen, Joe Saunders, Hatice Kose-Bagci, Kerstin Dautenhahn (2008) “Acting and Interacting like me? A method for identifying similarity and synchronous behaviour between a human and robot”, IEEE IROS Workshop on "From Motor to Interaction Learning in Robots", Nice, France, 26 September 2008.

Task 5N.3: Implementation of gesture communication interaction games integrated with IHA architecture demonstrable on a humanoid robot, release in the iCub software repository and demo on the iCub.

The Interaction History Architecture (IHA) has been one of UNIHER’s key contributions to the iCub software repository as a generic architecture for development and interaction histories implemented on the iCub. Information-theoretic foundations of development previously for WP3 were augmented to include temporally extended sensorimotor experiences. Based on its sensorimotor experiences (as defined in previously delivered implementations of IHA plus deliverables D6.3 and D6.4), augmented by short-term memory capacity, the humanoid robot is able to develop behaviours or new action sequences via social interaction and reinforcement via social cues. The new IHA was released at the end of 2009, incorporating several new modules and improvements. The state-of-the-art implementation potentially supports the behavioural development, switching between acquired behaviours, including acquisition of peek-a-boo and engagement in drumming interactions. This implements episodic memory and prospective action-selection within a constrained temporal horizon, providing functional support for several aspects of Cognitive Development (WP2) and allowing the robot potentially to scaffold its development of behavioural competencies in a social learning context, while making use of forgetting and merging of some experiences.

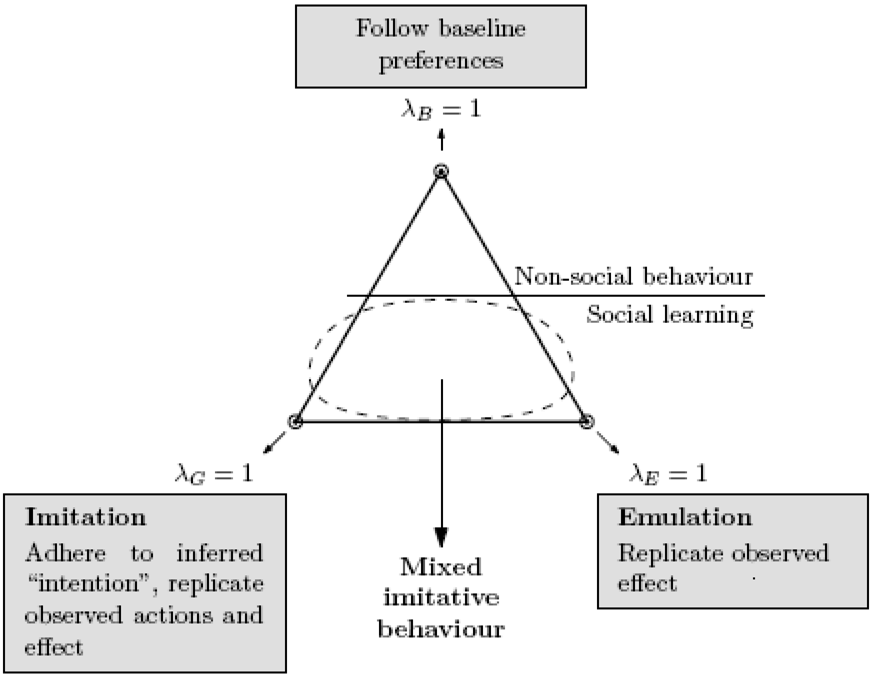
Software development of this extended Interaction History Architecture, augmented by the use of other modules (e.g. updated AudioAnalyser, Drum-mate, gaze tracking) in the RobotCub software repository are demoed as part of D5N.2, and this software has been delivered as a software release in the iCub repository as part of deliverable D5N.3 (which also includes updates and documentation for D6.3 (UNIHER) and other relevant modules).

Frank Broz, Hatice Kose-Bagci, Chrystopher L. Nehaniv, Kerstin Dautenhahn, (2009), "Learning behavior for a social interaction game with a childlike humanoid robot", Social Learning in Interactive Scenarios Workshop, Humanoids 2009, Paris, France, 7 December, 2009.

IST

During the fifth year of the project, IST developed the following research activities:

Continuation of the work on modelling social learning with the University of Uppsala – The contribution of this work is to provide a unified model that captures different imitation-like behaviours using a unique framework based on inverse reinforcement learning. We show that different behaviours like: emulation, stimulus enhancement, contextual learning and response facilitation, can be modelled under the same formalism. We also studied the specific advantages/disadvantages of each one.



We modelled typical behavioural switching experiments from psychology and have shown that our model can explain emulation to imitation transitions by weighting differently three sources of information (see figure above), imitation, emulation and baseline preferences. Some testable hypotheses were given by such model:

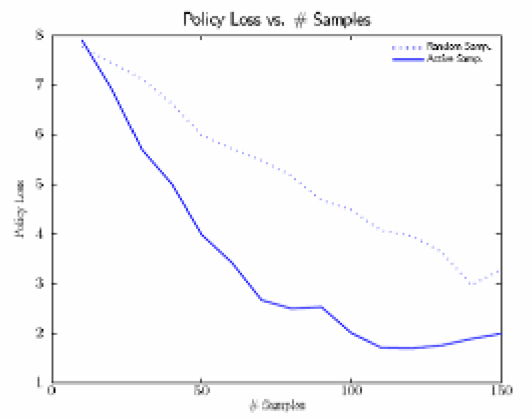
- Switching may be caused by different values given to social interaction or the value of the effect;
- When weighting only preferences and imitation, emulation can appear in intermediate values.

A Computational Model of Social-Learning Mechanisms. Manuel Lopes, Francisco S. Melo, Ben Kenward and Jose Santos-Victor. Adaptive Behaviour, in press, 2009.

Abstraction Levels for Robotic Imitation: Overview and Computational Approaches. Manuel Lopes, Luis Montesano, Francisco Melo and José Santos-Victor, in From motor to interaction learning in robots, in press, Springer Verlag, 2009.

Theoretical tools for learning from imitation – Under this topic, IST has investigated the use of inverse reinforcement learning as a tool for recovering the mechanisms underlying a demonstrated task. The contribution was to include the possibility for the learner to query the demonstrator for additional information, also known as active learning. This theoretical contribution aims at the development of learning algorithms able to function with complex tasks, high-dimensional data sets and limited data sets for learning.

Most of the imitation algorithms rely on (large) datasets acquired before learning. These datasets may not be the most informative ones and may as well be larger than necessary thus causing unnecessary cost. We developed an active learning approach to select the expected most informative samples and ask those to the demonstrator. By iterating through this process we can learn better policies with less data. As a by product, we can also assess the uncertainty on the policy at each state. The figure below shows typical gains that can be obtained with our method. Active learning can achieve the same policy loss with around 1/3 of the data.



Active Learning for Reward Estimation in Inverse Reinforcement Learning. Manuel Lopes, Francisco Melo and Luis Montesano. European Conference on Machine Learning (ECML/PKDD) Bled, Slovenia, 2009.

Affordance based word-meaning association (former WP6) – We have continued the work developed in the previous period, related to the association of words to the affordance model described by a Bayesian Network. We have improved the learning and clustering techniques and tested with new datasets. The approach allows for determining the association between verbal descriptions and actions. This knowledge can be used for planning robot actions from verbal instructions and improving speech perception skills using the scene context.

Affordance Based Word-To-Meaning Association, V. Krunic, G. Salvi, A. Bernardino, L. Montesano, J. Santos-Victor. International Conference on Robotics and Automation 2009, Kobe, Japan.

EPFL

In the last reporting period, work by EPFL was essentially devoted to bring together all the work and software developed during the first 48 months of the project to provide a demonstrator (Deliverable D5N.2) and software available to the community through the SVN repository (Deliverable D5N.3). Precisely, the demonstrator and software are based on statistical models for learning dynamics of motion from demonstration (Hersch et al, IEEE TRO, 2008) and on models for sensorimotor coupling for robust reaching motion (Hersch & Billard, Autonomous Robots 2008) and for estimating the body schema (Hersch et al, IJHR 2007).

All the work on which the software and demo are based made advances to the state-of-the-art in:

1. programming by demonstration by contrasting modelling of human motions through time-dependent and time-independent dynamical systems (Hersch et al, IEEE TRO, 2008)
2. in sensorimotor control, by proposing a generalized inverse kinematics method that avoids singularities (Hersch & Billard, Autonomous Robots 2008) and by offering a means to relearn the

body kinematics when the robot's end-effector are augmented, e.g. through the use of tools (Hersch et al, IJHR 2007).

In addition, important advances on the understanding of how one can encode efficiently movements in non-linear dynamical systems that achieve robustness in the face of temporal and spatial perturbation were done through the development of algorithm to ensure stable estimates of non-linear dynamical systems (Gribovsaka, Khansari & Billard, IJRR, submitted).

Work of EPFL within WP5N focused on the implementation of a demonstrator that combines both algorithms for learning from demonstration and robust control with algorithm for re-estimation the body schema developed during M1-48. Precisely, estimation of the position and orientation of the robot's arm was modelled as a joint probability distribution of the velocity and position of the end-effector and of the arm joints over time through Gaussian Mixture Models. Combining this with dynamical system control provides flexible reproduction of motion of the motion in task space while satisfying specific arm posture (e.g. specific orientation when approaching the target). Reproduction is robust in the face of perturbations, e.g. motion of the target during reproduction. The demonstrator consists of first training the robot to do a task requiring precise orientation and positioning of the end-effector. The robot is then given a tool that extends its end-effector. When reproducing the task, the robot fails to achieve proper orientation and positioning. Through a trial-and-error process in which the robot re-estimates its body schema and re-fines its knowledge of the task, the robot eventually manages to reproduce correctly the task.

E. Gribovskaya, M. Khansari and A. Billard. Learning non-linear multivariate dynamics of motion of robotics manipulators. International Journal of Robotics Research (submitted) 2009.

B. Petreska and A. Billard Movement Curvature Planning through Force Field Internal Models Biological Cybernetics, 100 (2009) 331-350.

Deviations from the project work-programme

None.

List of deliverables

Del. no.	Deliverable name	Workpackage no.	Date due	Actual/Forecast delivery date	Lead contractor
D5N.1	imitation & communication, report,	WP5	M65	M65	EPFL
D5N.2	Imitation & communication, demo	WP5	M65	M65	EPFL
D5N.3	Imitation & communication, software	WP5	M60	M60	EPFL

List of milestones

Milest one. no.	Milestone name	Workpackage no.	Date due	Actual/Forecast delivery date	Lead contractor
M4.3	Release of version 2.0 of the iCub software	5N	M65	M65	UGDIST

WP7 – Mechatronics of the iCub

Workpackage objectives

The objectives of WP7 for the entire duration of the project were:

- The realization of the first prototype of the iCub at month 30.
- The realization of the final prototype of the iCub at month 36.
- The realization of several copies of the iCub by month 65.

Effort for the last period is devoted mainly to the construction of the copies of the iCub for the Open Call while standardizing and documenting the assembly and construction methods. Some additional activities will be dedicated to debugging. In parallel, we will study specific improvements and continue the technology testing activities: for example in the field of impedance (force/torque) control.

The integration and assembly will continue through the supervision of TLR and the final integration of the mechanics with electronics and control with UGDIST and IIT. Contributions from all partners involved in the design are expected through frequent exchange of information and additional meetings (as during the design stage).

The long construction activity of the copies of the iCub accommodates a debugging period. During this period, parts might need to be rebuilt and solutions to unexpected problems found by redesign and additional testing. The mechanical solutions will be checked together with the final electronics and controller.

It is planned to complete the Open Call assembly approximately at month 64 (one more robot will be delivered with respect to what stated in the Implementation Plan M37-48). During the same period, the realization of two extra copies will be supervised to be allocated to two of the partners.

Active tasks

Task 7.1: Complete design of the iCub
Task 7.2: Debugging of existing components
Task 7.3: Realization of multiple copies of the iCub
An additional task will be undertaken by SSSA:
Task 7.4: Development of the hand sensory system
In this task sensors for the low-level control of manipulation will be developed and integrated in the SSSA hand (a variant, compatible version of the iCub hand). A controller using these sensors will be developed and tested. SSSA is building an iCub arm with the variant of the hand.
Task 7.5: Optimization and fine tuning of the electronics, wiring and assembly of the iCub. Debugging of pc104 interface card, design and fabrication of force/torque sensor control card, finalization of the hall-effect sensor acquisition card to be mounted on the hand, finalization of the plastic covers of the iCub. Documentation of this activity and inclusion into the main documentation site. This work will be the responsibility of IIT.
Task 7.6: Investigation on tactile sensors and artificial skin. Production of a first prototype of artificial skin (low resolution) and a fingertip, including electronics, sensors and software. This will be integrated a

posteriori into the robot design and possibly added to the 8 copies of the Open Call. This work will be the responsibility of IIT. At the minimum, we expect to integrate the fingertips in the iCub hands.

Progress towards objectives

Activities in WP7 were devoted along several lines of research including:

- Completion of the current release of the iCub (task 7.1);
- Debugging and optimization activities (task 7.2 and 7.5);
- Open Call (task 7.3);
- Implementation of tactile and force/torque sensing (task 7.4 and 7.6);

As per the specific objective SO4 also some new technologies were “probed” since they can be useful in the future development of the iCub. However, most of the activity in WP7 is now devoted to the debugging of minor issues as the robot is used more extensively, to the integration of components and the improvement of the assembly and wiring procedures. WP7 contributed also to:

> *SO-2: The finalization of the complete design, fabrication, assembly, test, and documentation of the iCub and its duplication in a number of copies for the winners of a competitive call. In particular, this includes the definition of the functional and technical specifications of the iCub mechanics, electronics and software architecture. By month 65, the goal is to have the complete validated design including: the iCub mechanics with 53 degrees of freedom (as per D7.1 and D7.5), control electronics, PC104 interface card, force/torque sensor feedback (not control) including miniaturized electronics, face and expression design, complete plastic covers. In addition, by month 65, up to nine iCub kits will have been fabricated to support the launch of the projects arising from the open call for new research (seven robots assigned as the result of the RobotCub Open Call and two internal to the Consortium).*

and the already mentioned SO4:

> *SO-4: Results of the testing of new technologies. Clearly, at this stage of the project, the result of this activity will not influence the actual iCub fabrication. It is important though to understand whether new components, compatible elements, sensors or motors will be available in the near future. These replacement components can go either in the direction of improving performance or in reducing the price of the robot.*

In the following, iCub versions have been defined as follows:
v1.0: the robot that has been produced for the Open Call;
v1.1: as 1.0 but with the addition of the force/torque sensors, full body covers, improved audio amplifier, position reading from the fingers and a set of small mechanical improvements;
v1.2: as 1.1 but with fingertips and palm tactile sensing (these are the robots for the ImClever project);
v2.0: under design, with full joint level torque control, tension sensors measurements and full-skin, improved electronics.

The main activities carried out by partners involved in WP7 are briefly reported.

UGDIST/IIT

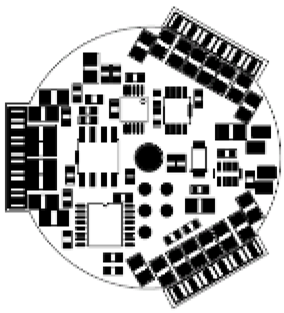
Force/torque sensors

iCub arms and legs mount a 6-axis force/torque sensor (FT sensor), which have been developed as a collaboration between Salford (now IIT) and IIT. Here we describe the main features of the sensor.

Mechanics

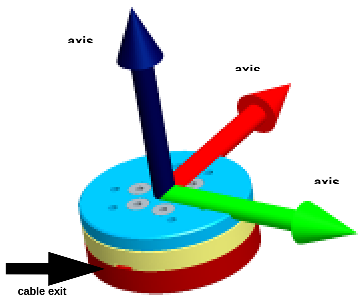
The mechanical solution follows standard rules for the design of the sensors. Three spokes mount two half Wheatstone bridges, each composed of two semiconductor strain gauges (SSG). Note that the sensing element is located between two flanges which link the sensors to the robot. The sensor production does not require any particular machining process, apart from an accurate strain gage bonding (Micron Instruments, USA).

Electronics



A 6 channel data acquisition board (STRAIN A/D board) is embedded into the force/torque sensor. The sensor mounts half of the Wheatstone bridge, while the STRAIN provides for the second half. Sampling of raw voltages is provided using a 16 bit A/D converter with a sample frequency of 1 kHz. Communication with the other boards (motor control boards or PC104) uses CAN bus. On the DSP, a calibration matrix is stored, and the resulting CAN message can be therefore made to contain raw forces and torques values (instead of the stain gauges direct readings).

Calibration



The FT sensor measures 6 independent voltage variations from a Wheatstone bridge. In order to convert the sensor output into the actual forces and torques acting on the FT sensor, calibration is required. The calibration matrix is a 6x6 matrix that accounts for a linear mapping between measured data and forces & torques. The figure to the right shows the reference frames used for force calibration. The calibration procedure consists in the application of known weights in linearly independent force configuration and least square fitting over a series of measurements. Empirical full scale values after calibration are here reported in the following table.

Fx [N]	Fy [N]	Fz [N]	Mx [Nm]	My [Nm]	Mz[Nm]
400	400	800	8	8	8

First use of the sensor is reported in WP3 for zero force control.

iCub updates (on version 1.0)

IIT has further worked on the improvement and debugging of the iCub along the following lines:

- Full body covers, including definition of attach points (screws), shapes, mechanical interference verifications, and limit check/verification (this task was developed in full collaboration with TLR);

- Face: re-engineering for production, including: materials of the face, skull, eyelids and light spreaders (eyebrows and mouth), general mechanical improvements of these parts;
- FT sensors as described above; in addition we have modified the mechanical design in order to improve the performance (stronger screws, precise torque estimation for mechanical coupling, etc.);
- Hands: new springs for improved phalanxes coupling (for underactuated mechanisms);
- Reworked tendon routing (in several places) to improve the duration of the steel cables (also in collaboration with TLR);
- Electronics: new insulated fixtures and spacers for all boards and wiring standardization;
- Improvement on the wiring and shielding of the joint encoders (magnetic disturbances), improving as a consequence the precision of movement and positioning of the robot;
- Protection (mechanical) of all AEA (hall-effect encoders) PCBs;

All documentation has been updated consequently. More importantly, the entire lower body CAD has been reassembled to bring it to the agreed quality standards which removed certain problems in managing and modifying the models. This last activity required considerable effort although it does not show up in the final robot construction (but it is important for the continuation and maintenance of the iCub development). The set of pictures below documents part of this activity.

Fingertips

We designed and realized several prototypes of a fingertip which includes a capacitive pressure sensor with 12 sensitive zones. It is naturally shaped and its size is small enough so that it can be mounted on the fingers of the iCub. As a result it is 14.5 mm long and 13 mm wide. The PCB with the electronics is included in the fingertip. It connects all the electrodes of the capacitive pressure transducer to an off-the-shelf capacitance to digital converter. The fingertip is made of silicone, which makes its surface and inner structure compliant and flexible. The transducer of the capacitive pressure consists of two conductive layers separated by a soft insulator made of silicone foam. The inner conductive layer is separated into 12 areas (see Figure 7), forming the taxels, acting as electrodes. The silicone layer, which compression is measured, is overall only 2mm thick in order to maintain a good spatial resolution. We use the silicone foam because it compresses easily after the first contact. This makes the sensor very sensitive to light touch. The foam is filled with bubbles that when compressed enough make the whole structure somewhat stiffer. A stronger force is then necessary to compress the silicone even more. This non-linearity is useful to enhance the range of measurable forces. Special focus has been paid on the production the 12 electrodes, as there production was intricate because of their small size. Also the support of the transducer can be flexible, which maximizes the compliance of the fingertip. We performed preliminary experiments with the first prototype showing the sensitivity of the sensor.

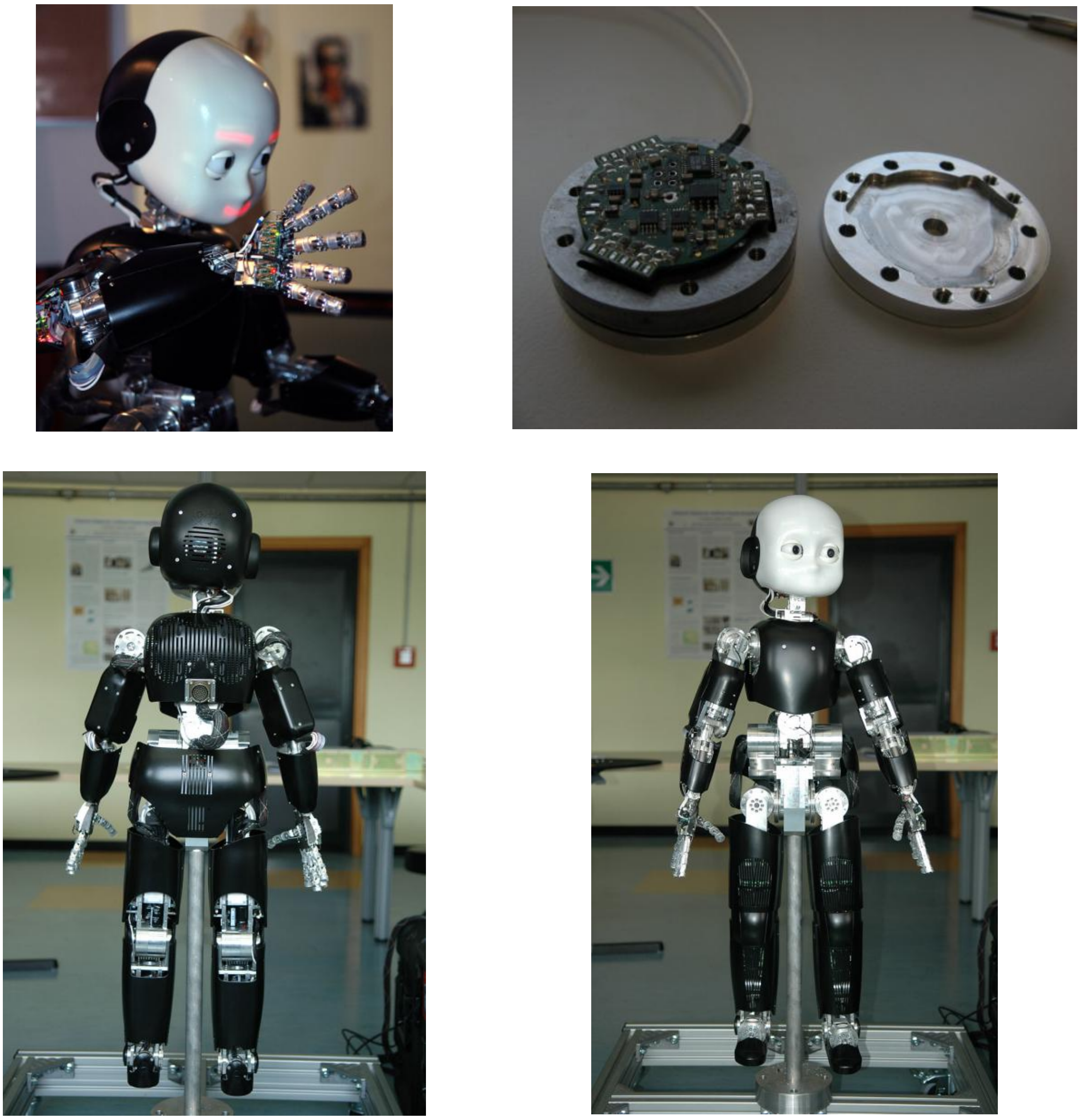


Figure 47: Some of the iCub improvements. (A) The hand with position sensor measurements; (B) The updated force-torque sensor; (C) The full body cover (back view); (D) The full body cover (front view) and new face engineering.

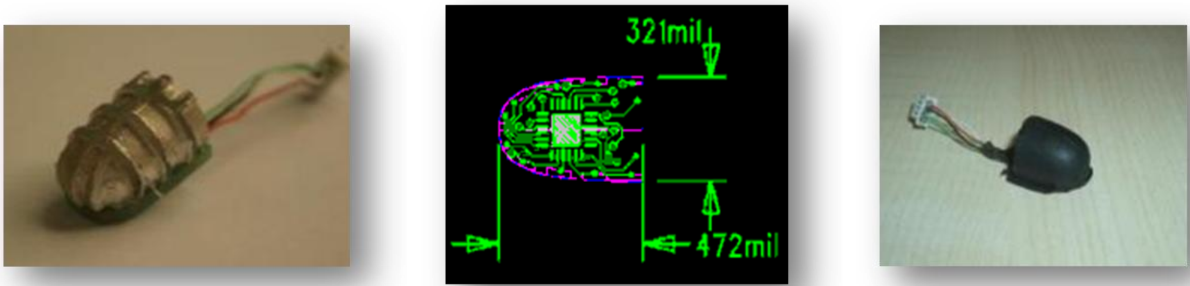


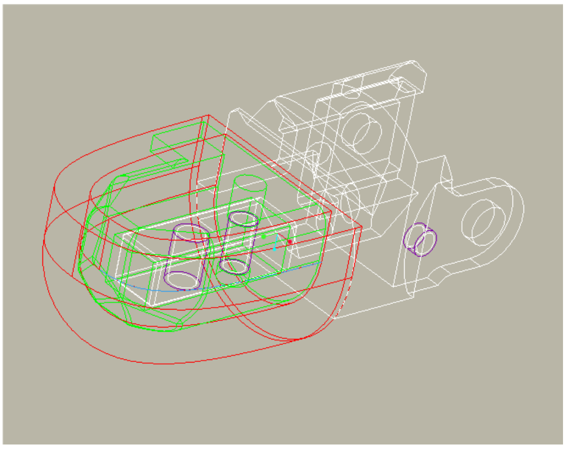
Figure 48: From left to right: the electrodes painted on solid plastic, the PCB layout (earlier version) and the fully coated fingertip (initial prototype).

In the last period, effort was devoted to:

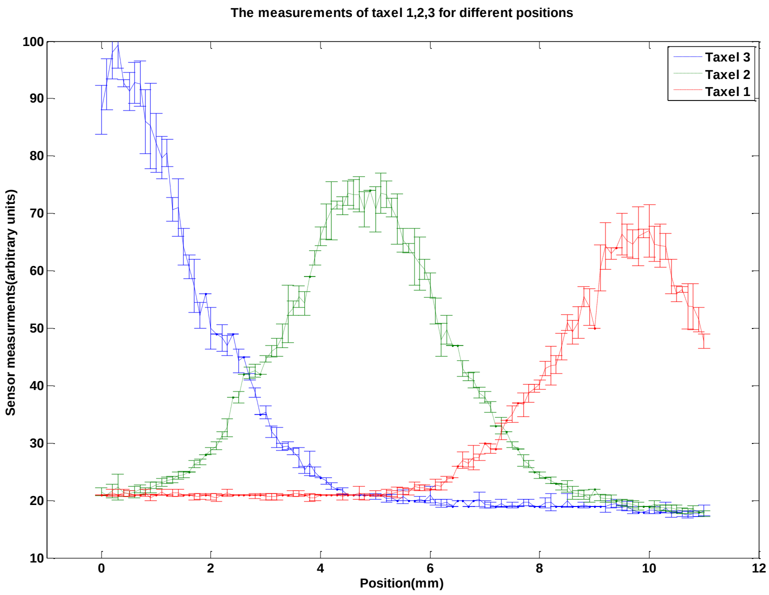
- Practical engineering of the fingertip for production;
- Modifications of the iCub hand for assembling the fingertips;
- Investigations into the materials (silicone) for improvement of dielectric constant;
- Repetitive testing and performance evaluation of the sensors.

The following pictures show the new sensor design using a folded flexible PCB wrapping the fingertip, some initial evaluation of the sensor performance using a robotized setup and the CAD design of the modified finger assembly. This latest version will be delivered in iCub v1.2.

(A)



(B)



(C)

Figure 49: (A) The latest implementation of the capacitive fingertip, for production reasons the solution based on conductive dyes was replaced by a flexible PCB; (B) A CAD picture of the new finger accommodating the fingertip sensor; (C) Spatial sensitivity of the fingertip: abscissa is the position of the probe (in mm), ordinates are the output voltages (0-5V) thus representing arbitrary units of pressure (not calibrated).

Alexander Schmitz, Marco Maggiali, Marco Randazzo, Lorenzo Natale and Giorgio Metta. (2008) A Prototype Fingertip with High Spatial Resolution Pressure Sensing for the Robot iCub. Proceedings of the 8th IEEE International Conference on Humanoid Robots (Humanoids08).

New motor group evaluation

This work was focused on the design and testing of an updated actuator group module which will form the actuation unit for the future robot upgrades. In particular the existing actuator group was enhanced with additional sensing components and new materials for the module structure were explored. The following sections introduce the details of these developments.

Enhanced position sensing

By evaluating walking motions it was found that for dynamic motions the 12-bit resolution (0.088°) of the absolute rotary position sensor (Hall effect sensors of AS5045 from Austria Microsystems) used in the iCub v1.0 (see above for definition of iCub version numbers) and located on the joint after the reduction drive was insufficient. Problems had arisen as the original angular velocity data based on the existing encoder signals is not ideal with the fidelity of the signal affected by the quality of the position sensor and the method used to generate the velocity signal, e.g. pulse counting or pulse timing. With the initial design the smallest detectable angular velocity obtained using the pulse count method is:

$\Delta q/Ts=0.088°/0.001s=88°/s$,

which is too coarse. Although this can be in some degree improved using averaging or filtering techniques a more radical solution is necessary to provide a better resolution velocity signal. To both improve the angular accuracy and velocity signal in the new prototype an additional 11bit incremental encoder is mounted inside the motor housing before the reduction drive (Figure 50).

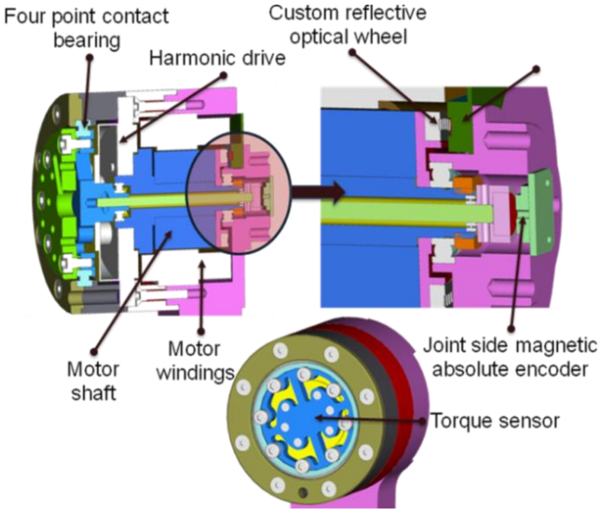


Figure 50: Section of the 3D mechanical assembly and mechanical parts of the updated motor/gearbox group.

In the new design the encoder disk and emitter-receiver with the integrated electronics (micro-e chip encoder) were placed inside the motor housing without the need to increase the size of the motor. Considering the 100:1 gear ratio provided by reduction drive the positional accuracy at the joint side is improved to 0.0017°. The minimum detectable angular velocity using the pulse count method now becomes $\Delta q/Ts=0.0017°/0.001s=1.7°/s$. The absolute encoder at the joint side is retained for calibration purposes. To validate the effect of the joint sensing improvements as discussed above two scenarios were evaluated. In the first case the low level joint control loop is closed on the joint side using the 12bit absolute magnetic encoder (current motor group). In the second scenario the joint control loop is closed using feedback from the incremental encoder which is mounted on the motor side (updated motor group). The tracking performance of one of the joints for a low frequency sinusoidal input (0.3Hz) is illustrated in Figure 51. This low frequency signal was selected to show the inability of the old prototype to accurately track low velocity profiles. The upper panel of Figure 51 shows significant fluctuations in the output trajectory both in the line and peak regions which were even visually evident when the robot was performing air walking trajectories. The main cause of these fluctuations is the friction in the harmonic drive gear which cannot be removed by increasing the damping gains due to the low quality of the velocity signal. In the second case (new motor prototype), Figure 51 lower panel shows that the output trajectory is much smoother without any obvious fluctuations due to the increased damping permitted by the higher resolution sensing.

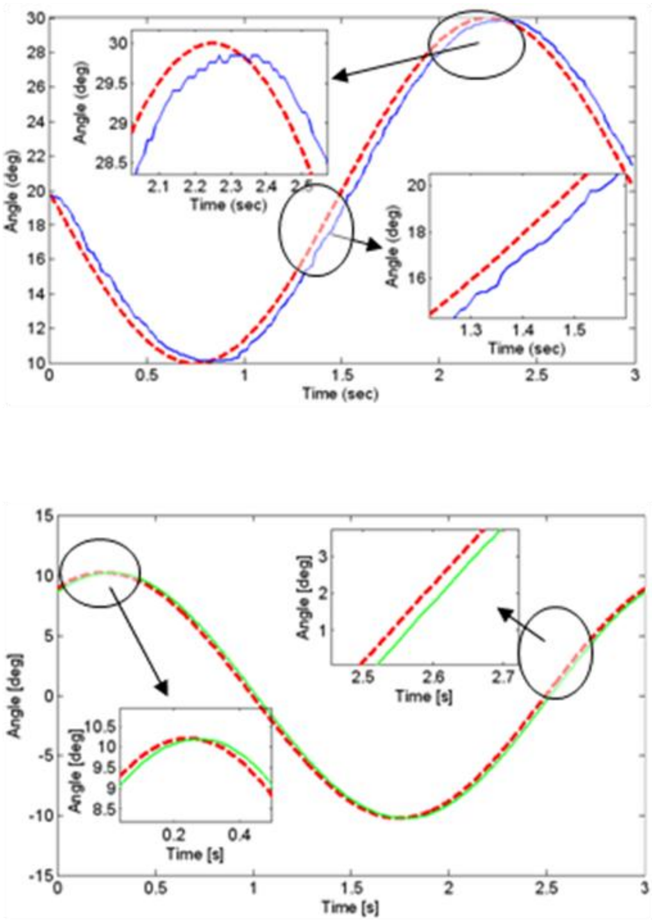


Figure 51: Joint tracking performance improvement.

Torque sensing

In addition to the enhanced position sensing, torque sensing was integrated within the new motor group as force control and not position control is the key technology for natural physical interaction for robots. In contrast, most humanoids, as the lower body of the iCub v1.0, are position controlled with high gain PD. More recent research has also focused on the use of individual joint torque control using software controlled active compliance or passive compliance. To achieve this research was directed into the integration of torque sensors. Since commercial motor torque sensors are both expensive and often not mechanically compatible (size, mechanical interface) with high degrees of freedom robots where space is limited a customized torque sensor with additional advantage of dimensional optimization was developed, Figure 52.

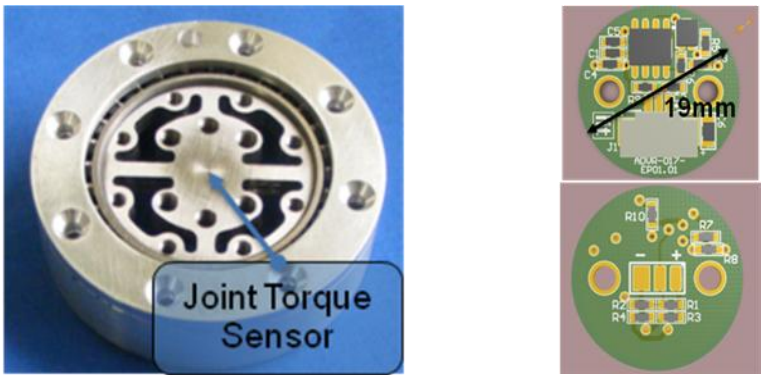


Figure 52: Structure of the joint torque sensor and the associated signal conditioning electronics prototypes.

The joint torque sensor is based on a four spoke structure mounted between the harmonic drive output and the output link. The strain is measured with semiconductor strain gauges and customized design electronics mounted close the motor.

Lightweight materials

In addition to the sensing additions further modifications to the motor group module aimed at investigating the feasibility of using new materials in the structure of the actuator group were investigated. The purpose was to reduce the weight of the module while maintaining the high power properties of the motor/gearbox assembly. Carbon fibre material was selected to replace some of the aluminium components of the motor assembly as shown in Figure 53. The parts were manufactured using mould fabrication techniques. To achieve the high tolerance requirements negative moulds were produced using the existing aluminium parts. Compared to the weight of the aluminium parts the weight of the carbon fibre parts was reduced by 47%.

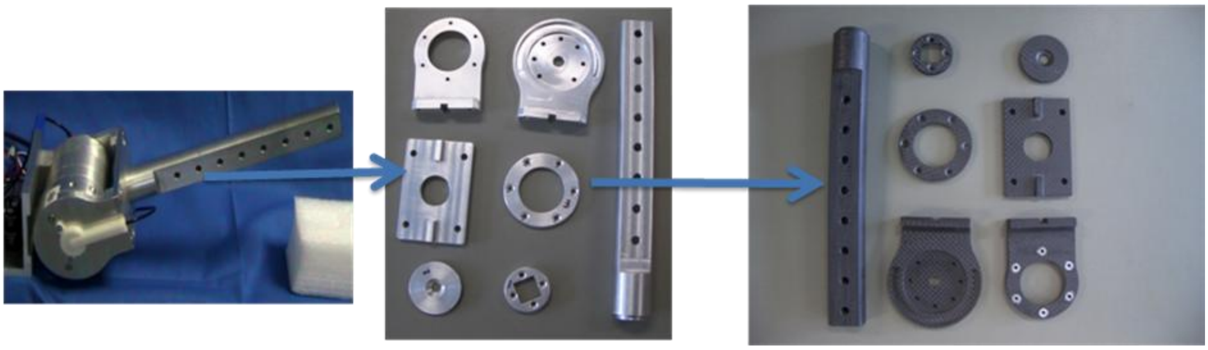


Figure 53: carbon fibre parts of the motor assembly.

N.G.Tsagarakis, Bram Vanderborght, Matteo Laffranchi and D.G.Caldwell, "The Mechanical Design of the New Lower Body for the Child Humanoid robot 'iCub' ", IEEE/RSJ International Conference on Intelligent Robots and Systems, IROS 2009, pp4962-4968.

N.G.Tsagarakis, Matteo Laffranchi, Bram Vanderborght, Darwin G. Caldwell, "A Compact Soft Actuator Unit for Small Scale Human Friendly Robots", IEEE International Conference on Robotics and Automation Conference, (ICRA 2009), Kobe Japan, pp4356-4362.

S. Davis, N.G. Tsagarakis and Darwin G. Caldwell. The Initial Design and Manufacturing Process of a Low Cost Hand for the Robot iCub. IEEE International Conference on Humanoid Robots, pp40-45.

Forearm redesign

This is joint work with TLR, see later for details.

Shoulder torque sensing

As part of the general improvements towards compliant control, a new activity has been undertaken for the design and integration of joint torque sensors in the upper body. These have been realized at the moment for the first four joints of the shoulder and elbow based on semiconductors strain gauges and by replacing a small number of mechanical parts.

Improved PC104 I/O card

As joint task between IIT and UGDIST, a new PC104 I/O card interface has been designed and it is now in advanced stage of design. This solves several issues but especially the bandwidth limitations of the CAN bus by increasing their number and therefore allowing partitioning the robot controller on several buses. In particular, major improvements are:

- 10 CAN bus ports
- Better sound amplifier with software-controllable gain, stereo
- Better PCI interface including DMA capabilities
- Improved buffering between the CAN drivers/microcontrollers and the PCI bus
- Dual microcontroller for CAN bus management, shared memory, etc.

The code for this new card is CFW-02 (replacing the current CFW-01a). It maintains the firewire interface as the previous version.

IST

During the fifth reporting period IST has not made further contributions to the hardware, other than providing assistance for the final tuning and duplication of the covers designed by IST during Y4.

SSSA

As part of WP7, a general control architecture has been developed and several low-level control modules implemented for the SSSA hands and updated following various hardware improvements. The grasping module presented interesting results especially thanks to the exploitation of the new cable tension sensors. Concerning advanced specific tasks, the strategy adopted for the recognition of object softness and texture is a novel issue in the development of humanoid robotics. In order to verify the controller features, experimental grasping trials have been performed. Based on the approximate percentage of utilization of the main grips in activities of daily living, seventeen different shape, size and weight objects have been chosen. The control strategy used in this simple, but robust controller allowed performing stable grasps in the 96% of the experiments. It has been presented an advanced task of object softness and texture recognition. In the SSSA hand a lot of efforts are dedicated to the development of a specific tactile sensor able to perform this discrimination. The experimentation of this advanced capability has already given several good results and a lot of excellent hints for future developments, even if the trials were aimed mainly to exploit sensor fusion in order to get qualitative results. The finger is actually able to discriminate not only if an object is soft or not, but also several intermediate classes of softness. The same consideration could be made for the object texture identification, even if the experimental results are not as accurate as for the object softness. From the point of view of a hardware developer, the choice of a fully underactuated finger does not avoid the use of a hybrid actuated finger. On the other hand, the additional degrees of mobility of a hybrid finger will make the fingertip touch the object always with a correct inclination and enable the system to achieve even better information from the sensors.

TLR

The main task of Telerobot during the reporting period was in supporting the continuous update of the robots (together with IIT), the mechanical assembly of the Open Call iCub's and debugging activities of various sorts. At the end of 2009, fifteen iCub's were assembled (and subsequently completed and delivered). These include 9 copies for the RobotCub project (4 for FP7 project ITALK, 1 for UGDIST and 1 for IIT).

This was achieved by carefully subdividing the mechanical production of the iCub's to different workshops which indirectly also helped to check the iCub mechanical documentation. In particular some tolerances across the iCub main joints were modified as a consequence of feedback from production. For example, the frameless motor tolerances are larger than initially expected (the motor documentation was mechanically incomplete). One particular set of motors were at their tolerance limits and this affected the integration of the motor groups requiring additional effort. A revised tolerance schema is now fully compliant with the new motor specifications (corrected). Shim rings are also added to assemblies that require tight overall dimensions (e.g. the hip or knee joint).

Resulting from feedback from IIT, the forearm design was upgraded with ring al little finger actuation redesign and crimp tendons on wrist pitch/yaw joint already made in the Y4 was further reviewed integrating absolute sensors on the two foremost wrist joint and modifying the proximal tendon routing on index and middle finger. This final design was realized and tested in Telerobot in this last period although it will not see integration until the next series of iCub's (version 2.0, see above). A prototype is at the moment under testing at IIT. Preliminary tests done in Telerobot on the modified forearm show higher reliability and easier integration: wrist tendon assembly was probably, before this improvement, one of the hardest tasks of the mechanical integration. Further tests are required before accepting these modifications (and possibly upgrading the existing iCub's).

The CAD of the fingertip design, wiring and mechanical assembly into the iCub hand has been integrated (revision of the fingertips and some minor modifications). Also in this case, this modification will only be available starting from iCub version 1.2 (as under construction for the FP7 ImClever project).

Deviations from the project work-programme

None.

List of deliverables

Del. no.	Deliverable name	Workpackage no.	Date due	Actual/Forecast delivery date	Lead contractor
D7.5	Status of the platform: major changes, debugging activities, problem report	7	M65	M65	UGDIST/IIT

List of milestones

Milest one. no.	Milestone name	Workpackage no.	Date due	Actual/Forecast delivery date	Lead contractor
M4.1	Open Call robot completed	7	M64	M65	UGDIST

WP8 – Open System: iCub

Workpackage objectives

The objectives of WP8 are:

1. Define the activity related to the creation, licensing, and distribution of the “Open Platform”.
2. Define the mechanical, documentation, and software standards to ensure the widest acceptability of the platform.
3. Help in defining the platform and coordinate with WP2 for requirements and WP7 for mechatronic and technological aspects.
4. Supporting the software development on the iCub and its architecture.

The activity of this Workpackage is devoted to the creation and support of the community of “end-users” of the “Open Platform”. In the initial phases of the project the main activity was directed to define and establish the infrastructure of the iCub initiative. In this respect, this Workpackage defined and supported the various iCub standards and requirements.

Although the work with WP8 is easily described amounting to a few sentences, its role should not be underestimated since one of the achievements of RobotCub as a whole is the creation of a community around a common platform. Especially important are the acceptance of the standards and the will of sharing upgrades and improvements within the community. The real measure of success is in our view mostly related to the possibility of creating a self-supporting initiative that will extend naturally well beyond the RobotCub project.

Also, this Workpackage will work on the definition of the licensing and legal aspects, in particular, when non-EU partners and/or collaborations are considered. Along the same line, collaborations with industries interested in the “packaging and re-selling” of the iCub will be thoroughly evaluated/considered.

The IIT took responsibility for the documentation of the iCub, organizing available information, keeping it up to date and making it easily accessible. It also supported the creation of simulation tools, specifically the design and realization of a first prototype of a simulation platform aimed at reproducing both the kinematics and the dynamics of the robot. The simulation might include the motors and electric apparatus of the robot, thus providing information about the energy flows during the robot functioning.

IIT’s effort was also directed to testing and delivering the 9 copies of the iCub (7 for the Open Call and 2 internal to the Consortium). IIT coordinated integration in order to proceed according to schedule: it took care of the final checks of the mechanical parts, of the fine tuning of the assembly, calibration, testing, and final delivery of the robots including a basic software level. IIT hosted the Open Call winners for various training activities (both mechanical and electronics) and organized training sessions on the effective use of the iCub software. Spare parts were purchased to continue the support of the iCub to the Open Call winners.

Active tasks

Task 8.2: Documentation of mechanical design and components.

Task 8.3: Documentation of the design of the electronics and components.

Task 8.4: Software documentation.

Task 8.5: Legal and administrative issues.

Task 8.6: Software Architecture.

Task 8.7: Preparation of the documentation for the duplication of the robot.

Task 8.8: Initial analysis of simulation tools.

Task 8.9: Open Call.

Progress towards objectives

Activities in WP8 have progressed in all active tasks, in particular:

- Task 8.2: by improving the mechanical design of several key components (as reported in WP7) and improving the overall level of the documentation. Considerable effort was spent in re-assembling the entire lower body structure to make it compliant to standards;
- Task 8.3: by improving the manual of the iCub with details of the production and documentation of single components;
- Task 8.4: by rewriting certain standard for software documentation and defining a new standard (based on XML) to described iCub “applications” (distributed applications running on the controlling cluster);
- Task 8.5: by evaluating the possibility of creating a legal structure for continuing the development on the iCub after the end of the project. Various small changes and updates were also implemented on YARP;
- Task 8.6: by building support and debugging applications such as a graphic visualizer for the iCub (kinematics), improving CAN loader performance, debugging firmware, improving the way applications are defined and managed, providing dynamic GUI generation for applications from XML files;
- Task 8.7: by communicating with the various providers and continuously improving the documentation;
- Task 8.8: by helping others in developing simulators for the iCub (especially the ITALK project and more recently ImClever);
- Task 8.9: by completing the Open Call robots and delivering the last one (to Urbana-Champaign, IL) in January.

This Workpackage has contributed also to the Milestone M4.2 by connecting YARP to other Open Source packages, by making YARP a valid alternative to non-iCub users, and posing the legal basis for the continuation of the RobotCub work beyond the end of the project.

UGDIST/IIT

Mechanical documentation (mentioned also in WP7)

The most relevant change to the documentation (besides being moved to a SourceForge SVN repository) is the entire lower body CAD re-assembly in order to bring it to the RobotCub quality standards. This removed certain problems in managing and modifying the CAD models (e.g. number of constraints in matching parts). This last activity required considerable effort although it does not show up in the final robot construction (but it is important for the continuation and the maintenance of the iCub and its future development).

Software architecture: YARP

During this period, YARP has been improved continuously. YARP version 2.2.5 was released on Dec 4th, 2009. This had math library improvements, an important fix for 64-bit Ubuntu 9.04, better C# support, better support for use of YARP without CMake, etc. Previous releases during the same period include a set of improvements to name client behaviour, support for Ruby, release of an optional new name server with Sqlite database support fixes for ACE library problems, fixes for locale issues, improvements to language bindings, improvements to a graphical viewer and to process management.

All significant changes to YARP are noted in a ChangeLog file, available here:

http://yarp0.svn.sf.net/viewvc/yarp0/trunk/yarp2/ChangeLog?view=markup

To show the level of community building with respect to YARP, note that 32 people are acknowledged in the 102 ChangeLog entries during the reported period: Alejandro R. Mosteo, Alessandro Scalzo, Alexandre Bernardino, Alexis Maldonado, Andreu Corominas Murtra, Andrew Stout, Arjan Gijsberts, Arnaud Degroote, Baris Akgun, Bruno Nery, Christian Wressnegger, Danilo Tardioli, David Vernon, Dimitri Ognibene, Francesco Nori, Frank Forster, Gianluca Massera, Giorgio Metta, Giovanni Saponaro, Jonas Ruesch, Kyron Du Casse, Lorenz Mosenlechner, Lorenzo Natale, Marco Barbosa, Pablo Urcola, Paul Fitzpatrick, Philipp Robbel, Sebastien Gay, Sergey Skachek, Severin Lemaignan, Stephane Lallee, and Ugo Pattacini.

The VVV09 RobotCub Summer School was held in the period from the 20th of July to the 29th. The school serves as an excellent yearly test for improvements to YARP/iCub, and as a source of direction for future effort. The goal is to remove obstacles to research and collaboration. Since the 2008 school, the use of YARP namespaces has been absorbed by the user community and has worked well for avoiding conflicts that used to occur in large groups. Some remaining problems were identified in 2009 and are being addressed via evolution of the name server and name client. A new name server has been released and is under user testing. It is intended to be a drop-in replacement for the existing name server which achieves two goals: to move information about the YARP network into a standard database (for persistence and ease of manipulation using external tools), and to make it easier for third parties to understand and modify the name server.

There have been improvements in all subsystems within YARP, but very few major API changes. Process management (“yarp run”), device compilation, math library wrappers, the standard image stream viewer, and documentation have all evolved steadily. Support for non-C++ languages has improved (especially Python, Java, and C#) and support for new languages have been added (Lisp, Ruby). Community support of OS X by users has strengthened and become more organized.

We strive to make YARP work well with the default configurations available in popular Linux distributions and Windows versions, while preserving support for older environments. This means that during the reported period, YARP – like Lewis Carroll's Red Queen – has had to do some running in order to stay in the same place, as the software in common use by our community evolved. The *robotcub-hackers* mailing list has been playing a very important role in letting the main YARP developers know what problems early adopters with the latest versions of everything were running into, and letting us get these problems fixed before they hit the main set of users who upgrade only upon need. Most problems were ACE-related. Examples: a misconfiguration of ACE semaphores that needed to be worked around, an ACE compile error with gcc-4.4, a tricky sign change in an ACE method return value, and other esoteric problems.

Compatibility libraries and support material for a legacy (pre-RobotCub) version of YARP, YARP1, were removed during this period. There are no known remaining users of YARP1. This opens the door for optimization of some key YARP protocols.

Use of YARP has grown during this period. YARP has been used extensively by the “Blender for Robotics” project (Blender is a free and open source 3D modelling and simulation application, becoming increasingly popular with roboticists).

http://wiki.blender.org/index.php/Robotics:Index

A user of Orocos, a framework for robot and machine control, created OroYarp an Orocos-YARP binding library, during this period.

http://robotis.onera.fr/orocos/oroyarp

The YARP project switched from using CVS repositories to using Subversion repositories, in tandem with a similar move by the ICUB repository (which was also moved in full to SourceForge using the project “RobotCub” created in 2005).

iCub architecture: application management

Our middleware, YARP, divides an application into a set of modules (processes) that intercommunicate via YARP *Port* objects. In practice, any reasonable application exploits this parallelism by dividing a complex task into a set of smaller entities. YARP formalizes (and iCub takes the same approach) this modularity by means of the *RFModule* class (in a tentative to make things uniform and more sharable). In addition each module can manage sets of parameters (arbitrary in number and type) that are required to configure its behaviour as defined typically by the developer of the module. For this purpose another class has been developed called *ResourceFinder*.

Modularity is achieved at three levels: i) C++ libraries: less common and mostly within groups; ii) iCub modules: quite common, across groups; and iii) defining applications (as defined later). This is done in an effort to push code reuse via high-quality documentation for modules and applications and supporting for remotization and automation.

By definition thus a module is an executable that performs a specific task, and whose interface is defined in terms of YARP ports. Granularity at this level can be quite fine. Behaviours are obtained by instantiating and connecting networks of modules (see Figure 54).

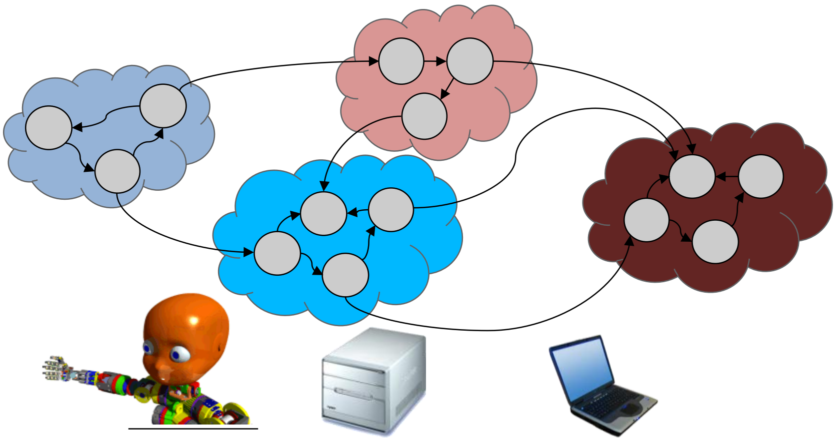


Figure 54: An example of sets of modules and their interconnections through YARP ports. Circles represents modules, the "clouds" represent a specific machine, directed arrows represent a connection between two YARP ports.

We defined a YARP (or iCub) application to be "a logical collection of modules with a particular purpose" (e.g. attention system, reaching, learning of affordances, drumming interaction history). In practice this has been implemented by defining the application as a collection of configuration files and a text description in the XML format. The XML file can then be automatically parsed and the application instantiated on a cluster of machines. Centralizing information into a single XML file enables the automatization of the start/stop/connect procedures and simultaneously centralization of parameter related information (which was otherwise left to the user to document the module details and providing examples). In practice since many parameters do not change often, providing a template XML for each application enables better code reuse at a higher level.

Therefore, applications are described using XML and through YARP an *application manager* performs common tasks e.g. starting modules with correct parameters, connect and disconnect ports, check dependencies. Further YARP now provides OS-independent remote execution (via specific client/server applications) with I/O redirection (YARP based terminals). The application manager is simply a parser of the XML specification of the application and is responsible of presenting it graphically to the user, who can then issue commands like "start", "stop", etc. The OS-independent remote execution facility is a new YARP feature which implements commands like "yarp run –on SERVER –cmd COMMAND [ARGLIST]" (please note that this syntax is not entirely correct) to run a command on a given machine with a set of arguments. The new *ResourceFinder* facility helps then in locating configuration files and other details of the current configuration (as for example which robot is being used). This helps in maintaining in sync the numerous iCub now available across Europe (and US).

The following Figure 55 shows an example of the GUI which is automatically generated (at run time) starting from its XML description. Clearly, this method of formalizing the description of the applications can be easily extended to visual programming languages where modules are recombined by the user via simple user interfaces. A simple additional parser can find all XML files and present them in another simple GUI which allows managing complex experimental scenarios with multiple applications.

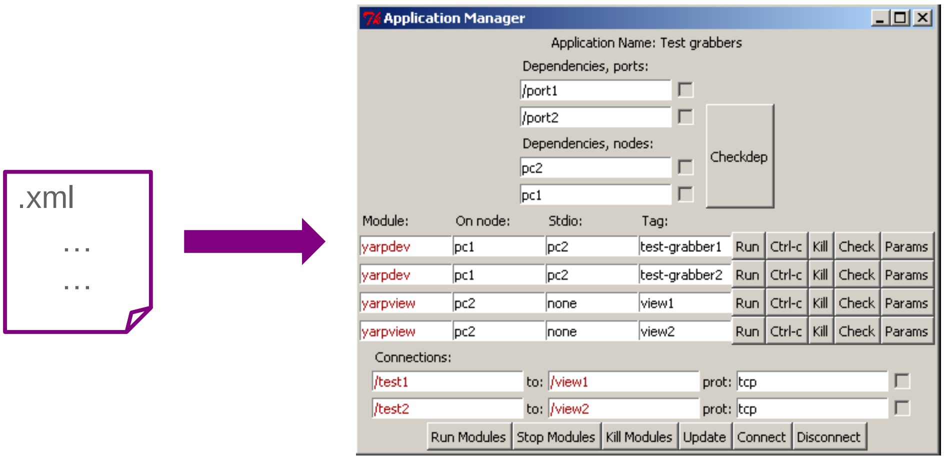


Figure 55: Example of the generated GUI from a simple "test grabber" application XML file.

Documentation

Documentation, in the form of the iCub manual (D8.5) and the mechanical/electronics file repository has been improved steadily.

In particular, the content of the iCub manual has been cleaned considerable although this is at the moment still in the form of a wiki website. Unfortunately, the wiki tends to become polluted quickly. We intend to move to a traditional manual in the future and maintain the wiki only for the transients and production of new documentation and tutorials.

The mechanical documentation has been improved and many additional details included in the CAD model of the iCub. At the moment, most of the “bill of materials” for building the iCub can be recovered from the CAD and subsequently searched in the manual. We added details of the suppliers for many commercial components (motors, gears, etc.).

IST

During the last period of the project, IST has again allocated a substantial effort to software development, according to the YARP architecture and contributions to the project demos. The implemented software (mostly related to vision and head control functions and affordances) is available in the repository and used during integration meetings in Genoa and during the RobotCub summer school. As in the previous period, the main contributed software was:

- head control
- affordances demo
- attention system
- tracking modules

TLR

Telerobot contributed (also with IIT) at the maintenance and improvement of the documentation (mechanical) of the iCub – now also available from the SourceForge SVN repository. Considerable, although not always very visible effort, has been allocated to the improvement of the CAD models and drawings. Even if it is reasonable that, for such an high number of drawings, further documentation reviews will be necessary in the future, the current mechanical documentation shows a good reliability (especially after the construction of many copies of the iCub).

Deviations from the project work-programme

None.

List of deliverables

Del. no.	Deliverable name	Workpackage no.	Date due	Actual/Forecast delivery date	Lead contractor
D8.5	Robot Documentation	8	M65	M65	IIT

List of milestones

Milest one. no.	Milestone name	Workpackage no.	Date due	Actual/Forecast delivery date	Lead contractor
M4.2	Open Source software self supporting (continuing)	8	M65	M65	IIT
M4.3	Release of version 2.0 of the iCub software	8	M65	M65	UGDIST

WP9 – Community Building and Self Assessment

Workpackage objectives

The objectives of WP9 are:

- Extend the base of knowledge for the definition of the iCub cognitive and mechatronic architectures and the adopted technologies by co-opting EU and non-EU scientists.
- Promote an international project on Embodied Cognition supported by national and international funding agencies.
- Monitor the advancement of the project toward the fulfilment of the project's objectives.
- Organize training and dissemination activities.
- Design, implement, and maintain a website to facilitate dissemination of all RobotCub-related information both between members of the consortium, and between the consortium and outside parties.

The work in this WP will be mostly related to organizations of meetings and workshop to reach the three objectives described above. The meetings will be organized as internal or open to the scientific and industrial communities. The management bodies relevant for this Workpackage are the International Research Panel (IRP) and the Board of Management (BM). Jointly they will decide on the topics to be discussed and the format of the meeting. The members of the IRP will be responsible of contacting funding agencies that may be interested in joining the International Project as well as industrial organizations potentially interested in monitoring the results of Robot-Cub. In consideration of the large investments that have been made in IIT, Department of Robotics, Brain and Cognitive Science in terms of instrumentation, human resources and facilities, IIT will set up a RTS within its Genoa premises. According to the project, the RTS will be specifically addressed the maintenance of the Open-system; the creation of a training facility in order to generate the conditions for student exchanges and collaborative research; gather research activities on original topics closely related to the Open-system.

Active tasks

Task 9.1: Internationalization: organize meetings with scientists and funding agencies.
Task 9.2: Training: organize training sessions for the project's participants as well as summer school on topics relevant to Cognitive Robotics.
Task 9.3: Assessment. At least once a year organize a formal assessment of the project.
Task 9.4: RobotCub website re-design and maintenance.
Task 9.5: Open call for research projects.
Task 9.6: Start up the Research and Training Site (RTS).
Task 9.7: Investigate the opportunity of commercialization and/or creation of a spin-off company for the iCub.

Progress towards objectives

This Workpackage goes beyond standard dissemination activities since in the case of RobotCub it is necessary to actively promote the platform to guarantee maintainability after the end of the project.
For Task 9.1, the iCub was on a live demo at IJCAI in Pasadena (CA) where many contacts with US companies (e.g. Barrett) and DARPA were made (DARPA has/had a program in Cognitive Systems and

Robotics). In Task 9.2, we organized the so-called "winter school" for the Open Call winners (but also generically for all iCub owners) and the fourth edition of the "summer school" near Genoa. We had a record of "good" applications in 2009 and we had to be selective eventually accepting 38 participants working on two iCub's in parallel and one head (with the usual support from simulators). For Task 9.3 we organized four meetings which were attended by all partners. Most of the time was devoted to software/integration related activities in preparation of the final review meeting. Task 9.4 progressed steadily and although the website did not evolve much, our "parallel" website http://www.icub.org has been growing considerably in content. Task 9.5 is the Open Call management. We have now completed the last robot of the Open Call (number 7), which is going to be delivered before the end of the project (some delay due to an unexpected debugging activity and the customs clearance for the US – which takes about four weeks). Task 9.6 continued as planned as IIT hosted several visits by partners for integration activities but also various visitors and other scientists interested in learning about the iCub. We also hosted a small workshop on software standardization inviting people from other projects (e.g. Paco+, the German Cotesys), companies (e.g. Willow Garage, US) and other research institutes (AIST Japan and the University of Tokyo). Further, we have contacts with Mathworks (Matlab) for studying the possibility of a serious integration of Matlab with the iCub architecture (this is all very preliminary). For Task 9.7, we progressed by seriously (i.e. with lawyers) evaluating various possible legal entities to manage the iCub IPR after the end of the project. Section 7 contains this legal response (though in Italian at the moment). We plan to try the creation of a European Interest Group based on the iCub.

Additional dissemination items are reported in sections 6.

UGDIST/IIT

These are some of the dissemination activities that were carried out by UGDIST/IIT during the last period:

- A journalist article was published on Nature (N. Nosengo. "Robotics: The bot that plays ball" Nature Vol 460, 1076-1078 (2009) doi:10.1038/4601076a);
- Participation to IJCAI, Pasadena, CA. The iCub was demonstrated at IJCAI in the States. This event was particularly interesting (workshop, large audience, funding agencies) and challenging from the organizational point of view (the iCub, spare parts, a small cluster of computers, and all debugging material travelled to IJCAI);
- Participation to the Genoa's science festival. The iCub was demonstrated at the Genoa's Science Festival which attracts thousands of visitors each year. It is a local event with a good international visibility. The Honda Asimo's show was also in the program of the festival.
- Participation to the ICT 2008 in Lyon. The iCub was demonstrated at the ICT conference in Lyon where the iCub stand was shortlisted as best 10-stands over 200 participants (although we did not win);
- Participation to the Futuro Remoto science festival in Naples: the iCub was demonstrated at the Futuro Remoto science festival (Nov 2009) in Naples. Representative from the Commission visited the stand (we had a live tracking and reaching demo for three consecutive days);
- Special session on "cognitive architectures" at ICDL (Shanghai): Giorgio Metta, Tamim Asfour (Univ. of Karlsruhe) and Gordon Cheng (TU Munich) organized a special session at the International Conference on Development and Learning in Shanghai, China.

- Workshop on “cognitive vision” organized at IROS 2009 St. Louis: Giorgio Metta, Barbara Caputo (IDIAP Switzerland) and John Tsotsos (York Univ. Canada) organized a workshop on Cognitive Vision at the IROS conference (St. Louis, US). Giorgio Metta was also an invited speaker at a Autonomous Mental Development workshop at the same conference.
- Giorgio Metta, Gordon Cheng, Tamim Asfour, Barbara Caputo and John Tsotsos are organizing a special issue on “Representations and Architectures for Cognitive Systems” in the IEEE Transactions of Autonomous Mental Development (2010): http://www.liralab.it/specialissue/tamd.htm
- A partial list of press and media appearances include:
    - Los Angeles Times;
    - Several Italian newspapers (e.g. La Repubblica);
    - Le Figaro (France);
    - Italian TV (Rai1, Canale5, Rai3);

  Some of these articles can be found at the following URL: http://www.iit.it/en/robotics-brain-and-cognitive-sciences/labs/cognitive-humanoids-lab/humanoids-lab-in-the-press-old.html
- Euronews released two videos about the RobotCub project which can be also found on YouTube at the following URL:
    - http://www.youtube.com/watch?v=pRxUVya_rk4&feature=PlayList&p=15D55F44D7517AA5&playnext=1&playnext_from=PL&index=5
    - http://www.euronews.net/2009/09/30/the-robot-that-can/
- Invited talks at: ICRA (workshop), IROS (workshop), IEEE-RAS Intl. Conference on Humanoid Robots (Workshop), Univ. of Southern Denmark (Odense), Univ. of Birmingham, CogX project Summer School (Stockholm), Microsoft Research (Redmond).

UNIHER

UNIHER took part in the following dissemination events (selected):

Chrystopher L. Nehaniv, Invited Keynote Lecture at EU Commission Event Research Opportunities in FP7 ICT Challenge 2: Cognition, Language and other Interfaces and Robotics - Imperial College of Science & Technology, London, UK, 11 December 2008. This lecture showcased the iCub robot and related work of the Adaptive Systems Research Group work on EU projects RobotCub, LIREC, eCircus, IROMEC, and ITALK. We also took the opportunity to organize an ad-hoc live demo there of the RobotCub iCub robot in Prof. Murray Shanahan's lab there where an iCub had just arrived.

Hatice Kose-Bagci, “Drum-mate: A Human-Humanoid Drumming Experience”, Computer Science Department, METU, Ankara, Turkey, 08 May 2009 (invited talk)

Frank Broz, “The Role of Social Interaction in Developmental Robotics”, invited talk, Autonomous Mental Development for Intelligent Robots & Systems workshop, IROS 2009, St. Louis, Missouri, October 11, 2009 and organized the following symposium:

Frank Broz, AAAI - Spring Symposium 2010: It’s All in the Timing: Representing and Reasoning about Time in Interactive Behaviour workshop, Stanford University, Palo Alto, California, March 22–24, 2010.

IST

IST has contributed to WP9 along the following lines:

- Demonstration of the iCub demo on affordances during the Y4 review
- Reimplementation of several modules of the affordances model to make it more modular and to be run in a more integrated fashion.
- Development of methods for object recognition in the ego-sphere
- Joint work with SSSA in models for tracking in the presence of occlusions
- Joint work with Uppsala on modelling social behaviours
- Work on learning sensory-motor maps,
- Software development for the iCub platform under YARP.
- Collaboration in the duplication of the platform.

TLR

Telerobot supported the Open Call training sessions (assembly and mechanical maintenance). Telerobot also supported researchers of other groups working on possible design improvements.

UNIZH

Lectures given by UNIZH members that involved a discussion on the iCub or more in general about the RobotCub project:

1. On the role of embodiment in enactive behaviour (tentative title). Invited keynote lecture at the “Enactive 2008 Conference”, Pisa, November 2008.
2. Self-organization, embodiment, and biologically inspired robotics. Invited keynote lecture. Darwin Days, Oslo, February 2009.
3. Artificial Intelligence. Samstagsuniversität, Bern, February 2009.
4. Embodied intelligence. Scuola Superiore Sant'Anna, Pisa, Italy, February 2009.
5. Cognition -- the interaction of brain, body, and environment. Invited keynote lecture. Third International Conference on Cognitive Science, Tehran, March 2009.
6. Embodied intelligence. FET 2009 Conference, Science Beyond Fiction, Prague, 2009.
7. Embodied intelligence. Invited keynote lecture at the 20th Anniversary of AI in Japan, Nagoya University, October 2009.
8. Self-organization, embodiment, and biologically inspired robotics. Keynote lecture, Lausanne, Switzerland, EPFL, Robotics Research Day, April 2009.
9. The four messages of embodied intelligence. Swissnex Fifth Anniversary Celebration, Singapore, July 2009.
10. The four messages of embodiment -- how the body shapes the way we think. Hosei University, Tokyo, October 2009.

11. Verkörperte Intelligenz und die Menschenwerdung der Maschine. Invited lecture at Volkshochschule Zürich. December 2008.

12. On embodied intelligence, bio-robotics, and human-centered machines. Invited lecture at Symposium on Robot Dreams. Kunstmuseum Graz, July 2009.

Deviations from the project work-programme

None.

List of deliverables

Del. no.	Deliverable name	Workpackage no.	Date due	Actual/Forecast delivery date	Lead contractor
D9.2	Material produced for the training activities	9	M65	M65	UGDIST
D9.3	Progress report on Internationalization activities	9	M65	M65	UGDIST

List of milestones

Milestone no.	Milestone name	Workpackage no.	Date due	Actual/Forecast delivery date	Lead contractor
M4.2	Open Source software self supporting	9	M65	M65	UGDIST

5. Status of deliverables and milestones

Deliverable number	Title	Description
D2.1	A Roadmap for the Development of Cognitive Capabilities in Humanoid Robots.	This is the final update of the Cognitive Roadmap. This deliverable is a written report.
D2.2	Software Implementation of the iCub Cognitive Architecture (version 2.0).	This deliverable is a report (manual) and demo (software) of the iCub Cognitive Architecture, release 2.0 (release 1.0 was delivered at M48).
D3.6	Software implementation of the phylogenetic abilities specifically for the iCub & integration in the iCub Cognitive Architecture.	This deliverable collects all contributions to the D2.2 from Workpackage 3 (sensorimotor coordination). In practice, this is a report and demo (manual and software) of the experiments on sensorimotor coordination and elements of the Cognitive Architecture as identified in D2.1. This deliverable has been made into a Wiki page which contains links to the software modules/applications (running on the iCub and committed to the iCub repository) and links to technical papers and videos.
D3.7	Results from Electrophysiological study of human sensorimotor representations.	This deliverable is a report on the experiments concerning the study of human sensorimotor representation. Thanks to UNIFE, RobotCub had the unique chance of access data of electrophysiological recording in humans during surgery. This deliverable reports about these studies.
D3.8	Demo of the iCub crawling and switching to a sitting position.	This is a demo of the iCub crawling controllers.
D4.1	Results of experiments on affordant behaviours.	This deliverable is made of two components: a report on the experiments on learning and detecting affordances, and the demo of the same experiments on the iCub.
D4.2	Software for the iCub & integration in the iCub Cognitive Architecture.	This deliverable item is the software contribution of Workpackage 4 to the Cognitive Architecture (see D2.2).
D5N.1	Imitation and communication for the iCub.	This report of the new Workpackage (WP5N) describes the experiments on imitation and communication.
D5N.2	Imitation and communication on the iCub.	This is the demonstration of the experiments described in D5N.1.
D5N.3	Imitation and communication software release for the iCub.	This is the software contribution of Workpackage 5N to the Cognitive Architecture described in D2.2 and

		represents also the demo of D5N.2 and reported in D5N.1.
D7.5	Status of the platform: major changes, debugging activities, problem report.	A description of the iCub final specifications.
D8.5	Robot Documentation.	The latest version of the iCub manual which is available online (Wiki pages). This is the ultimate collection of documents describing hardware and software of the iCub.
D9.2	Material produced for the training activities.	Description of the activities organized for training. RobotCub has organized its annual Summer School and a number of additional training events especially to iCub owners.
D9.3	Progress report on Internationalization activities.	Dissemination about the iCub and RobotCub has been solid during the last period of the project. This is a report of the activities.

All deliverables have been completed.

Milestone number	**Milestone title/name**	**Comments**
M4.1	Open Call robot completed, due M64	The last Open Call robot (number 16 in the production line) was delivered in January 2010, slightly delayed with respect to schedule because of an unexpected (thermal problem) with a new CPU and the time required for clearance from the US customs.
M4.2	Open Source software self supporting (continuing), due M65	The Open Source software will stay in existence and developed on IIT support until a legal entity for managing the iCub IPR is formed. New projects (e.g. ITALK) will support development in the interim.
M4.3	Release of version 2.0 of the iCub software, due M65	A new set of iCub “applications” has been released and is available as usual from the iCub SVN repository. The demonstrations at the review meeting will present this software.

All milestones have been achieved.

6. Dissemination and use of knowledge

Scientific publications

1. Alaerts K, Senot P, Swinnen S, Craighero L, Wenderoth N, Fadiga L. Force requirements of observed object lifting are encoded by the observer’s motor system: A TMS-study. European Journal of Neuroscience (submitted).
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4. Caselli, L., Oliynyk, A., Gesierich, B., Craighero, L., and Fadiga, L., Visual feedback from the own acting hand modulates the activity of grasping neurons in monkey premotor area F5. Journal of Neurophysiology (submitted).
5. Censolo R, Craighero R, Ponti G, Rizzo L, Fadiga L. Prosocial attitude modulates muscle activity in a simple coordination game. Social Neuroscience (submitted).
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16. Fadiga L, Craighero L, D'Ausilio A. Broca's area in language, action, and music. Ann N Y Acad Sci. 2009 Jul;1169:448-58.

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Technical reports

70. Martinez, H., Lungarella, M., and Pfeifer, R. (2009). Influence of the Sensor Morphology in the Generation of Coordinated Behavior as a Function of Information Structure. Technical Report University of Zurich.

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Theses

Naeem Assif Mirza, Grounded Sensorimotor Interaction Histories for Ontogenetic Development in Robots PhD awarded 2008.

Dorothee Francois, Facilitating play between children with autism and an autonomous robot, PhD awarded 2009.

Qiming Shen, Motor interference and behaviour adaptation in human-humanoid interactions, PhD thesis to be submitted in 2010.

Exploitable Knowledge and its Use

The RobotCub project is dedicated to the production of free-available open source results license under the GNU General Public Licence. Consequently, all RobotCub results are amenable to exploitation according to the terms of the license.

Dissemination Activities

See also section on WP9 and especially the online deliverable 9.3 which contains details of the dissemination activities of RobotCub.

Press (selected)

- EPFL's research on the iCub is featured in a radio documentary on IEEE spectrum (http://spectrum.ieee.org/tag/icub)
- Portuguese National Television (SIC) : Futuro Hoje – Science dissemination program (April 2009)
- Portuguese National Television (SIC Notícias): Exame Informática – Informatics dissemination program (May 2009)
- Euronews: Innovation days in Lisbon, (June 2009)
- Suisse TV show Science Suisse. Die Intelligenz des Körpers. November 16th, 2008.
- Hjärnan i focus på spädbarnslabbet. Horisont Uppsala Universitet 2009.
- Hjärnan utvecklas i samspel med barnets handlande.(2009) Tvärsnitt 3:09.

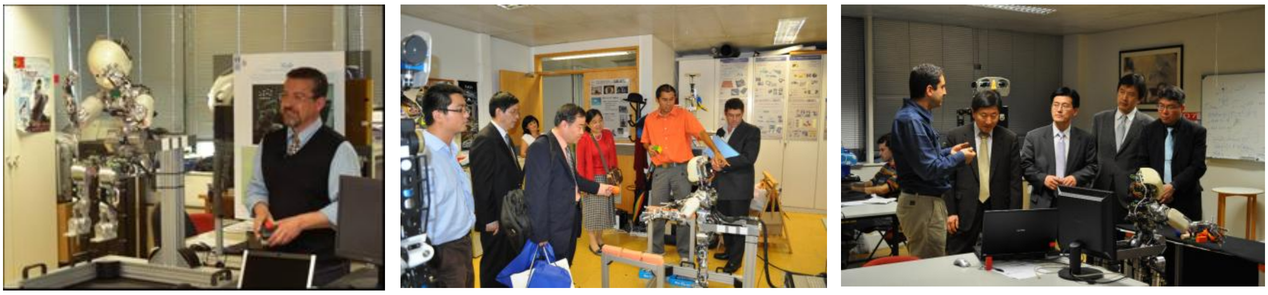

Figure 56: The iCub demonstrated for delegations visiting IST. Centre: President of the University of Ningbo, China, visiting IST in April 2009; Right: the president of the Hankyong National University, Korea during a visit to IST in December 2009.

Films

The iCub appears on a documentary movie (filmed in part during the 2008 RobotCub Summer School) "Plug & Pray" (working title: The Sorcerer's Apprentice) directed by Jens Schanze (http://www.maschafilm.de). This will appear at the international competition of the Biarritz Film Festival (http://www.fipa.tm.fr) in France. The festival starts Jan. 26th and ends Jan. 31st 2009.

Brief Synopsis of the film

Since antiquity, humankind has dreamed of creating intelligent machines. The invention of the computer and the breathtaking pace of technological progress appear to be bringing the realisation of this dream within our grasp. Scientists and engineers across the world are working on the development of intelligent robots which are set to become part of all areas of human life. Yet the ultimate vision goes a lot further: the merger of man and machine, to throw off the biological shackles of evolution and finally make eternal life a reality. What are the promises being made by scientists? What are the consequences for humankind? The film immerses itself in a world in which computer technology, robotics, programming, neuroscience and developmental psychology merge. We visit the world's leading experts in their laboratories in Japan, the USA, Italy and Germany. And yet of all people, one of the pioneers of computer development and artificial intelligence, former MIT professor, Joseph Weizenbaum, has become one of the harshest critics of his colleagues' visions of technological omnipotence. Unimpressed by a zeitgeist characterised by a seemingly unstinting devotion to progress he keeps asking the same question over and over again: Do we need all this?

7. Other issues

iCub IPR management after the end of the project. An informed lawyer opinion has been requested by IIT (reported below – in Italian at the moment of writing).

L'Istituto Italiano di Tecnologia (d'ora in avanti: IIT) chiede il mio parere in ordine all'individuazione della forma organizzativa ed associativa più opportuna per la costituzione di un soggetto giuridico attraverso il quale provvedere alla gestione della piattaforma software denominata "icub".

ANTECEDENTI

Il software icub è stato realizzato, nell'ambito del FP7 della Commissione Europea - settimo programma quadro per la ricerca, all'interno del progetto RobotCub, da parte di un consorzio cui hanno aderito partners pubblici e privati italiani ed europei.

Il termine previsto per la conclusione del progetto RobotCub è fissato al mese di dicembre p.v., momento in cui cesserà anche la validità del contratto di consorzio (di seguito "CA") all'uopo costituito.

Al fine di portare avanti, anche successivamente alla conclusione del CA, una serie di attività legate alla gestione, upgrade e diffusione della piattaforma software "icub" (di seguito le"Attività"), è stata manifestata da alcuni partners chiave, già presenti nell'originario consorzio, l'esigenza di provvedere ad individuare le modalità più opportune per tale scopo, attraverso la costituzione di un nuovo soggetto giuridico cui demandare lo svolgimento di alcune attività del consorzio ormai in via di scioglimento.

OBIETTIVI

Dai dati che mi sono stati forniti gli obiettivi che i partners del CA si propongono sono, tra l'altro, quelli di provvedere a gestire:

- la titolarità dei diritti di copyright del software icub;
- la redistribuzione del software con licenza gpl oppure lgpl oppure entrambe;
- l'instaurazione di un archivio, contenente la documentazione ed il supporto del software icub;
- la raccolta dei contributi dei programmatori da tutto il mondo che abbiano interesse allo sviluppo del software icub;
- il coinvolgimento di istituti di ricerca ed aziende private, sempre al fine di consentire la più ampia partecipazione allo sviluppo ed upgrade del software.

In sintesi, il nuovo soggetto – senza finalità di lucro – che si intende costituire dovrebbe rappresentare un'interfaccia unica ed un unico punto di riferimento per il software icub. Tale soggetto dovrebbe, altresì, essere in grado di partecipare ai prossimi programmi quadro europei, successivi al "FP7".

La nuova iniziativa dovrebbe, infine, essere posta all'attenzione degli officer della UE, durante il review meeting finale che si terrà nel gennaio 2010.

MODELLI COMUNITARI *VS.* MODELLI NAZIONALI

La "storia" del software icub, indissolubilmente legata al progetto RobotCub nel cui ambito è stato sviluppato, unitamente agli obiettivi che si intendono perseguire nell'immediato futuro depongono entrambi per una scelta che ricada su strumenti "europei" di integrazione giuridica.

Rispetto ai modelli nazionali, infatti, quelli transnazionali a dimensione comunitaria presentano il pregio di avere una disciplina in larga misura omogenea in tutto il territorio della Unione, assicurata da Regolamenti e/o Direttive la cui adozione (quando richiesta) da parte degli Stati membri è obbligatoria. Il che, evidentemente, facilita l'ingresso – e, dunque, l'integrazione – di associati aventi distinte nazionalità, in quanto consapevoli delle regole – ulteriori, rispetto a quelle desumibili dall'atto costitutivo – che governeranno l'attività del nuovo soggetto giuridico. Il modello o strumento comunitario si lascia preferire, poi, in situazioni come quella di cui qui ne occupa, in quanto, è quasi superfluo sottolinearlo, perfettamente compatibile con i progetti di ricerca banditi dalle Istituzioni europee, il cui *favor* verso forme di associazione di matrice comunitaria è ben noto agli operatori.

INDIVIDUAZIONE DEL MODELLO COMUNITARIO PREFERIBILE

Tre sono i modelli che teoricamente potrebbero essere utilizzati ai fini che qui specificamente interessano: la società europea (SE); la Società Cooperativa Europea (SCE); il Gruppo Europeo di Interesse Economico (GEIE).

L'analisi che seguirà parte dal presupposto che sia l'IIT il soggetto "capofila" del progetto, e che quindi i tre modelli abbiano sede amministrativa in Italia.

Di queste tre, può senz'altro scartarsi la prima (*i.e.*, la SE). Il Regolamento CE 2157/2001 (integrato, poi, dalla Direttiva 2001/86/CE, sul coinvolgimento dei lavoratori all'interno della SE), prevede, infatti, per tale modello organizzativo, un capitale sociale minimo pari a 120 mila euro, che appare esuberante per il programma di attività che il nuovo soggetto ha intenzione di porre in essere. D'altra parte, la disciplina applicabile alla SE è modellata sulla falsa riga di quella propria delle società per azioni (così, ad esempio, per quel che concerne la quota di partecipazione al capitale sociale; il sistema di amministrazione e controllo; ecc.), che risulta, ai fini degli obiettivi che si intendono perseguire nella specie, del tutto inadeguata e inutilmente complessa.

Il campo può dunque tranquillamente restringersi agli altri due modelli summenzionati.

A. La SCE, la cui disciplina "generale" è contenuta nel Regolamento CE n. 1453/2003 e nella Direttiva 2003/72/CE sul coinvolgimento, in essa, dei lavoratori – e, per quanto riguarda specificamente l'ordinamento italiano, nella Circolare del Ministro dello Sviluppo Economico 30 giugno 2006, n. 9203 – si inserisce nel complesso ed articolato mondo della cooperazione.

Anche la SCE si caratterizza per il c.d. "*principio della porta aperta*", essendo il numero di soci ed il capitale della stessa variabile (art. 1, co. 2 Reg. 1453/2003), e per la *gestione di servizio a favore dei soci cooperatori* («La SCE ha per oggetto principale il soddisfacimento dei bisogni e/o la promozione delle attività economiche e sociali dei propri soci, in particolare mediante la conclusione di accordi con questi ultimi per la fornitura di beni o di servizi o l'esecuzione di lavori nell'ambito dell'attività che la SCE esercita o fa esercitare. La SCE può inoltre avere per oggetto il soddisfacimento dei bisogni dei propri soci, promovendone nella stessa maniera la partecipazione ad attività economiche, come precedentemente indicato, di una o più SCE e/o di cooperative nazionali. La SCE può svolgere le sue attività attraverso una succursale.» art. 1, co. 3). Anche per la SCE vale la distinzione tra cooperative a mutualità prevalente (quelle società che svolgono la propria attività prevalentemente con i propri soci) e quelle a mutualità non prevalente (quelle che svolgono la loro attività prevalentemente con i terzi), in dipendenza delle clausole inserite nello statuto (artt. 2513 e 2514 c.c.).

Lo statuto della SCE prevede la responsabilità limitata dei soci partecipanti, salvo diversa disposizione dell'atto costitutivo (art. 1, co. 2 Reg.).

Il numero minimo di soci fondatori è 5 (siano essi persone fisiche o giuridiche), residenti in almeno due Stati membri (art. 2, co. 1), ed il capitale sociale minimo è fissato in 30 mila euro (art. 3, co. 2 Reg.).

Il controllo governativo sulle SCE è disciplinato dalle norme dello Stato membro in cui ha sede la SCE. In Italia, tale controllo è rimesso al Ministro dello Sviluppo Economico, salvo che la sede sia in una regione a statuto speciale (nel qual caso il controllo è affidato alla Regione), oppure nelle province di Trento e Bolzano (nel qual caso è affidato alla Provincia). E' inoltre prevista la partecipazione necessaria dei lavoratori nelle scelte strategiche della SCE, secondo quanto stabilito dalla Direttiva 2003/72/CE.

Il sistema di amministrazione e controllo è modellato sulla falsa riga di quello già previsto nel nostro ordinamento per le s.p.a.: lo statuto può quindi scegliere tra il sistema monistico (che prevede l'assemblea dei soci ed un consiglio di amministrazione che elegge, al suo interno, un comitato per il controllo della gestione); quello dualistico (assemblea dei soci; consiglio di sorveglianza, eletto dall'assemblea dei soci; consiglio di gestione, eletto dal consiglio di sorveglianza); oppure quello tradizionale (assemblea; consiglio di amministrazione, o amministratore unico; collegio sindacale, se supera certi parametri dimensionale, altrimenti revisore esterno).

La SCE con sede in Italia deve destinare il 30% degli utili conseguiti a riserva legale (comb. disp. art. 65, co. 1 Reg. e 2545-*quater* c.c.) ed il 3% ai Fondi mutualistici *ex* art. 11 l. n. 59/92; mentre in caso di scioglimento dovrà devolvere il patrimonio netto residuo (una volta soddisfatti i creditori e rimborsati i soci) ai fondi mutualistici *ex* art. 11 l. 59/92, se a mutualità prevalente (in caso contrario potrà distribuire tra i soci il residuo).

Da quanto sin qui sinteticamente esposto in ordine allo statuto della SCE, sembra che anche questo modello organizzativo non soddisfi in pieno le esigenze connesse allo sviluppo del progetto icub. In particolare, appare eccessivamente procedimentalizzata la costituzione della SCE e, soprattutto, l'attività che la stessa intende svolgere: i modelli di amministrazione e controllo; il coinvolgimento dei lavoratori; i controlli della P.A.; la disciplina del capitale, dei ristorni e delle devoluzioni ai fondi mutualistici, sembrano costituire, invero, dei vincoli non necessari rispetto agli obiettivi che si intendono conseguire.

Complessità che emerge limpidamente dalla consistenza, anche solo quantitativa, del *corpus* normativo di riferimento: il Regolamento n. 1453/2003 conta 75 articoli, ai quali vanno aggiunti – in una delicata opera di armonizzazione e coordinamento – gli articoli del c.c. dedicati alle società cooperative (artt. 2511-2545-*octiesdecies*); quelli della Direttiva sul coinvolgimento dei lavoratori; nonché le varie disposizioni relative ai fondi mutualistici e la circolare del Ministro dello sviluppo economico del 2006.

B. Decisamente più appetibile è la terza opzione, quella offerta dal GEIE, del quale, in questa sede, pare opportuno offrire un quadro istituzionale più approfondito.

a) Introduzione.

Prima di passare all'analisi degli aspetti che qui più immediatamente interessano, è opportuno soffermarsi su quella che potremmo definire la *ratio* del GEIE, ossia le necessità che lo strumento comunitario ha inteso soddisfare.

Allo scopo, risulta di fondamentale importanza la lettura dei due primi considerando del Regolamento comunitario n. 2137/85 del 25 luglio 1985 (in proposito va subito ricordato che il valore ermeneutico dei Considerando comunitari è diverso e ben più incisivo del valore del tutto marginale che, nell'ambito dell'ordinamento interno, viene dato alla intenzione soggettiva del legislatore quale emergente dalle relazioni di accompagnamento ai disegni di legge).

In questi due considerando si menzionano:

- l'instaurazione ed il buon funzionamento di un mercato comune che assicuri condizioni analoghe a quelle esistenti in un mercato nazionale;
- creazione, nell'ambito del mercato comune, di un contesto giuridico che faciliti l'adattamento delle attività alle condizioni economiche della Comunità;
- la necessità che le persone fisiche, le società e gli altri enti giuridici possano effettivamente cooperare oltre le frontiere, superando le difficoltà di carattere giuridico, fiscale o psicologico che tale cooperazione può incontrare.

L'intento è quindi quello di porre a disposizione degli operatori economici comunitari uno strumento con disciplina unica, e quindi per tutti agibile nei rapporti di cooperazione con soggetti di altri paesi comunitari senza la preoccupazione di trovarsi a dover scegliere ed a sottostare ad una disciplina di un istituto totalmente sconosciuto in quanto proprio di uno specifico ordinamento nazionale.

Per soffermarci ancora un momento sui dati della pratica, va detto che il GEIE non ha avuto quell'espansione che forse ci si aspettava, anche se, va sottolineato, nel 2005 sono stati costituiti in Italia ben 40 nuovi GEIE, su un totale, aggiornato al marzo del 2006, di 136 ancora operativi. Lo Stato comunitario che più di tutti ha utilizzato lo strumento del GEIE è il Belgio (alla stessa data ne risultavano operanti 331), seguito dalla Francia (241), dalla Germania (177), e così via, per un totale complessivo nell'ambito della Comunità Europea di 1464 GEIE.

Le cause di questi risultati, non certo brillantissimi (anche se, ripeto, sembra che ultimamente le cose stiano cambiando), possono essere le più varie e certo non è facile riuscire ad individuarle con esattezza: posso solo segnalarne alcune.

Così:

- la scarsa pubblicità e la conseguente disinformazione degli operatori;
- la non chiara collocazione della nuova figura nel quadro dei tradizionali istituti privatistici;
- la mancanza di familiarità giuridica e pratica con strumenti giuridici «transnazionali»;
- la responsabilità illimitata per le obbligazioni assunte dal GEIE dei membri partecipanti.

b) Fonti normative e disciplina applicabile.

Il GEIE, come anticipato, trova la sua fonte disciplinare più importante nel Regolamento CEE n. 2137/85. Ai sensi dell'art. 1, § 1 reg. «Il presente regolamento stabilisce le condizioni, le modalità e gli effetti secondo cui sono costituiti i gruppi europei di interesse economico». A sua volta, l'art. 2, § 1 dello stesso Regolamento stabilisce che «Fatte salve le disposizioni del presente regolamento, la legge applicabile, da un lato, al contratto di gruppo, tranne per quanto riguarda le questioni di stato e di capacità delle persone fisiche nonché di capacità delle persone giuridiche, e, dall'altro, al funzionamento interno del gruppo, è la legge nazionale dello Stato in cui si trova la sede stabilita dal contratto di gruppo». In Italia la «legge» di cui fa menzione l'art. 2, § 1 del Regolamento è il d.lgs. n. 240/1991, il cui art. 1 così recita: «Al Gruppo europeo di interesse economico previsto dal regolamento 2137/85 del Consiglio del 25 luglio 1985 ed avente sede nel territorio dello

Stato, si applicano, per quanto non disposto dal suddetto regolamento, le disposizioni del presente decreto».

Le norme del regolamento assumono, al di là del rango sovraordinato, rilievo centrale sia perché contengono la parte comune ed inderogabile e i precetti da applicare in caso di assenza di manifestazione di volontà negoziale, sia perché forniscono i criteri per la individuazione delle restanti regole applicabili.

Per l'attuazione del regolamento comunitario il legislatore italiano si è trovato a dover emanare:

- *a*) norme «*delegate*», in conseguenza di espressi rinvii del legislatore comunitario ai diritti nazionali;
- *b*) norme «*opzionali*» da emanare eventualmente sulla base di scelte rimesse ai legislatori dei Paesi membri ai fini del raccordo della disciplina del GEIE con altri istituti; infine
- *c*) norme «*ulteriori*», comunque non in contraddizione con il contenuto e gli obiettivi del regolamento.

Esempi del primo caso sono le norme relative alla registrazione; esempi del secondo, sono le norme che consentono l'amministrazione del GEIE ad una persona giuridica e l'esclusione di diritto del partecipante dichiarato fallito; esempi del terzo tipo, infine, sono le norme sulla liquidazione, sul fallimento e sul trattamento tributario del GEIE.

c) *La natura giuridica del GEIE.*

Il GEIE, come detto, è uno strumento di cooperazione e di collegamento nell'azione economica tra soggetti di Paesi comunitari diversi. Si tratta di un istituto a matrice *contrattuale*. Dal punto di vista economico, dunque, il GEIE può essere assimilato ad altre figure di collaborazione internazionale tra imprese: si pensi, ad esempio, alle associazioni temporanee di imprese e alle c.d. *joint ventures*.

Dal punto di vista giuridico, invece, le cose cambiano notevolmente. In tutti i casi di cooperazione internazionale citati, infatti, la sostanza del vincolo collaborativo è esclusivamente di tipo *obbligatorio*: nel contratto tra i paciscenti si esaurisce la fonte disciplinare dei rapporti interni. Non vi è alcuna istituzionalizzazione, ossia la creazione di un ente metaindividuale: nei casi appena segnalati, le manifestazioni esterne dell'attività, qualora vi siano, sono di scarso rilievo e si risolvono negli schemi del mandato, oppure della contitolarità.

Il GEIE, all'opposto, ha, ai sensi dell'art. 1, § 2 reg. «la capacità, a proprio nome, di essere titolare di diritti e di obbligazioni di qualsiasi natura, di stipulare contratti o di compiere altri atti giuridici e di stare in giudizio». Il GEIE, quindi, è centro di imputazione di atti e rapporti giuridici: ed è ente che non si risolve nella sommatoria dei singoli partecipanti. Una volta regolarmente costituito ed iscritto il GEIE è un soggetto giuridico.

Il legislatore italiano non ha preso posizione circa l'attribuzione o meno al GEIE della personalità giuridica, malgrado il regolamento lasciasse tale scelta ai legislatori nazionali: si deve dunque ritenere che, al pari dei consorzi (con attività esterna), il GEIE non ha da noi personalità giuridica.

Infine, il GEIE assomiglia per molti versi ai nostri consorzi con attività esterna: sul punto, però, si tornerà successivamente.

Nel GEIE, come vedremo, un ruolo fondamentale viene svolto dal contratto: il legislatore comunitario, prima, e nazionale, poi, ha voluto concedere ai partecipanti un'ampia autonomia statutaria, tale da consentire agli stessi di godere di un agile strumento di cooperazione modellato sulla base delle esigenze aziendali di ciascuno. E si tratta di un «contratto associativo con comunione di scopo con rilevanza esterna», analogo, ancora una volta, al contratto di consorzio con attività esterna italiano.

d) La costituzione del GEIE: forma, pubblicità e requisiti soggettivi.

Ai sensi dell'art. 2 d.lgs. «Il contratto di GEIE e le relative modifiche devono essere fatti per *iscritto, a pena di nullità*».

Per quel che concerne il contenuto del contratto di GEIE, l'art. 5 reg. stabilisce gli elementi minimi che debbono figurare nell'accordo (scritto), tra cui particolare importanza rivestono l'*oggetto*, la *sede* e la *denominazione del gruppo*. Sul primo (l'oggetto), parleremo diffusamente nel prosieguo: qualche considerazione può qui essere svolta per la sede e la denominazione del gruppo.

L'indicazione della *sede* del gruppo nell'ambito del contratto è elemento fondamentale, atteso che da tale decisione dipende essenzialmente la parte di disciplina applicabile al GEIE non direttamente ricavabile dalle norme del Regolamento. Peraltro, la discrezionalità delle parti nella scelta della sede non è senza limiti. Ai sensi dell'art. 12 reg., infatti, «La sede menzionata nel contratto del gruppo deve essere situata nella Comunità economica europea. La sede deve essere fissata:

i. nel luogo in cui il gruppo ha l'amministrazione;

ii. oppure nel luogo in cui uno dei membri del gruppo ha l'amministrazione centrale o, se si tratta di una persona fisica, l'attività a titolo principale, purché il gruppo vi svolga un'attività reale».

Con riferimento alla denominazione, l'art. 5 reg., lett. a), si limita a stabilire che la stessa (che può consistere in una espressione di fantasia) deve essere preceduta o seguita dall'espressione «Gruppo europeo di interesse economico» o della sigla GEIE.

E' altresì prevista l'*iscrizione* del GEIE, a cura degli amministratori entro trenta giorni dalla stipulazione del contratto, presso il registro delle imprese nella cui circoscrizione il GEIE ha sede (art. 3 d.lgs.). Infine, è prevista la pubblicazione (sempre a cura degli amministratori) nella Gazzetta Ufficiale dei dati rilevanti ai fini della individuazione del GEIE, nonché la pubblicazione nella Gazzetta Ufficiale delle Comunità Europee della costituzione e (successivamente) della chiusura della liquidazione (art. 4 d.lgs.).

Dal canto suo, il Regolamento stabilisce che «coloro che intendono costituire un gruppo devono stipulare un contratto e procedere alla iscrizione prevista dall'art. 6» (art. 1, § 1, secondo periodo).

Ai sensi dell'art. 4 reg. possono essere membri di un GEIE le società, gli altri enti pubblici o privati, costituiti conformemente alla legislazione di uno Stato membro e che hanno la sede sociale o legale e l'amministrazione centrale nella Comunità; nonché le persone fisiche che esercitano un'attività industriale, commerciale, artigianale, agricola, una libera professione o prestano altri servizi nella Comunità.

Com'è evidente, la norma comunitaria è talmente ampia da comprendere qualsiasi attività economica e qualunque struttura all'uopo creata per esercitarla (in Italia, dunque, imprenditori individuali e collettivi, liberi professionisti, enti pubblici o privati).

L'art. 4 reg. continua precisando che un gruppo deve essere composto almeno da due società o enti giuridici aventi l'amministrazione centrale in Stati membri diversi; oppure, da due persone fisiche che esercitano un'attività a titolo principale in Stati membri diversi; o, ancora, da una società o altro ente giuridico e da una persona fisica, di cui il primo abbia l'amministrazione centrale in uno Stato membro e la seconda eserciti la sua attività a titolo principale in uno Stato membro diverso.

Dunque, come si è più volte accennato, il contratto di GEIE suppone la partecipazione di persone fisiche od enti residenti in Paesi diversi della Comunità. Va anche aggiunto che il Regolamento comunitario lasciava ai legislatori nazionali la possibilità di limitare il numero dei soggetti partecipanti ad un GEIE a 20 e di escludere, per motivi di ordine pubblico, alcune categorie di soggetti dalla partecipazione al GEIE: il legislatore italiano non ha tuttavia ritenuto opportuno limitare né quantitativamente né qualitativamente la partecipazione al nuovo strumento di cooperazione comunitario.

e) Lo scopo-mezzo (oggetto) e lo scopo-fine del GEIE.

Passiamo ora ad analizzare lo scopo-mezzo, ossia l'oggetto, l'attività dallo stesso esercitabile, e lo scopo-fine del GEIE.

Il GEIE, come detto, costituisce un gruppo associativo: come tale è destinato quindi a svolgere un'attività comune nel senso di attività di cooperazione riferita al gruppo in quanto tale. La finalità associativa non riguarda peraltro l'esercizio di tale attività comune: questa infatti deve necessariamente collegarsi all'attività economica singola dei membri del gruppo e può avere soltanto un carattere *ausiliario* rispetto a quest'ultima (art. 3, § 1 reg.). Il fine essenziale dell'attività comune si delinea così nel senso di realizzare una forma di mutualità pura a servizio delle economie dei singoli e può avere esclusivamente uno scopo di agevolazione, sviluppo e miglioramento dei risultati dell'attività economica dei singoli membri. Ne consegue che il GEIE non può mai avere lo scopo di realizzare profitti per se stesso (art. 3, § 1 reg.). E', in altri termini, connotato essenziale della fattispecie, non derogabile dai legislatori nazionali, il carattere ausiliario dell'attività comune rispetto alle attività ed alle economie dei singoli membri, cui quell'attività si ricollega. Coerente con tale connotato è l'assenza di scopo lucrativo comune. Ciò che risulta pienamente compatibile con il programma di attività che il costituendo soggetto dovrebbe svolgere.

Sempre restando in tema di oggetto del GEIE, merita attenzione l'affermazione del considerando n. 5 del regolamento, che sembra precludere al GEIE attività sostitutiva di quella dei membri. Se l'attività del gruppo deve collegarsi a quella dei membri con il fine di migliorare o sviluppare la medesima o i suoi risultati, non sempre è peraltro agevole distinguere l'attività in aiuto dei membri da quella "in luogo" dei membri. L'integrazione o il prolungamento dei cicli produttivi potrebbero nella realtà sottendere la prestazione di un servizio sia a chi non sarebbe in condizioni di svolgerlo (generando una logica di ausiliarietà) sia a chi invece avrebbe tale possibilità (risultando quindi in tale seconda ipotesi potenzialmente sostitutivi).

Io direi che sul punto le norme del regolamento dovrebbero essere interpretate in modo non restrittivo: direi, cioè, che in linea di principio non sia vietato al GEIE di svolgere anche attività sostitutiva di quella dei membri. Sembra peraltro certo che il carattere ausiliario dell'oggetto del GEIE, se non esclude quindi in assoluto la sostituzione in fasi delle attività economiche dei partecipanti, deve peraltro comportare un rapporto di funzionalità con tali attività, che non possono essere totalmente assorbite ed anzi devono mantenere un ruolo prevalente. In ciò del resto si esprime il ruolo di "cooperazione", che non può mai tradursi in unione con assorbimento delle individualità dei membri del gruppo.

Ciò porta ad assimilare il GEIE ai nostri consorzi e ad allontanarlo dalla figura societaria: ciò che, nell'ottica che qui più interessa, si inserisce perfettamente nel solco della continuità con l'attività (precedente) che ha portato allo sviluppo del software icub.

f) L'organizzazione dei poteri all'interno del GEIE.

Ancorché di carattere ausiliario l'attività del GEIE è attività propria, distinta da quella delle imprese che ne fanno parte e comporta, quindi, la previsione di un'organizzazione per lo svolgimento di tale attività, organizzazione che assume rilevanza *esterna*.

La particolare rilevanza dell'organizzazione comporta la previsione di organi del gruppo. L'art. 16, § 1 reg. prevede che «organi del gruppo sono i membri che agiscono collegialmente e l'amministratore o gli amministratori. Il contratto di gruppo può prevedere altri organi; in tal caso ne stabilisce i poteri».

La scelta di limitare al minimo la disciplina legislativa circa il funzionamento del GEIE è in sintonia con quella italiana in materia di associazioni e fondazioni, per le quali l'art. 16 c.c. rinvia all'atto costitutivo ed allo statuto in merito alle "norme sull'ordinamento e sull'amministrazione". Di conseguenza, per quello che concerne l'organizzazione interna del GEIE, l'autonomia negoziale espressa nella fase della costituzione o successivamente a mezzo delle scelte dei membri può sia agire sulle figure di organi previste arricchendone la disciplina, sia introdurre figure nuove. E' possibile, ad esempio, prevedere un organo di controllo che svolga funzioni analoghe al nostro collegio sindacale; oppure un organo per la composizione delle liti tra i partecipanti, analogo al collegio dei probiviri, proprio delle imprese cooperative.

E' quindi lasciata alle parti la massima flessibilità nello strutturare la funzionalità del gruppo, fermo restando che una funzione amministrativa, distinta da quella deliberativa interna, è comunque essenziale per il GEIE e, quindi, devono essere previsti uno o più soggetti amministratori legati da un rapporto organico con il gruppo.

g) L'organo deliberativo.

Nell'art. 16, § 1 reg. si qualificano come "organo" del GEIE "i membri che agiscono collegialmente". La norma successiva dell'art. 17 reg., dopo aver previsto come criterio normale il voto per partecipante, salve deroghe che pur attribuendo più voti a singoli membri comunque non devono permettere a qualcuno di disporre della maggioranza dei voti, distingue le ipotesi in cui è richiesta l'unanimità da quelle in cui l'unanimità può essere derogata dal contratto di gruppo.

Nel primo gruppo rientrano le delibere aventi ad oggetto: la modifica dell'oggetto del gruppo; la modifica del numero di voti attribuito a ciascun partecipante; la modifica delle condizioni di adozione delle decisioni; la proroga di durata del gruppo.

La disciplina del procedimento attraverso cui i membri del gruppo deliberano è rimessa all'autonomia statutaria, sicché non vi è imposizione del metodo assembleare (convocazione-riunione-discussione-votazione), ben potendo i membri del gruppo esprimere il proprio voto ad es., per fax, in videoconferenza, attraverso consultazioni scritte ecc. E' dunque astrattamente possibile che i partecipanti al GEIE non si riuniscano mai fisicamente, come avviene oggi per molte decisioni in seno alla s.r.l..

Quanto detto non è chiaramente di ostacolo, pur nel silenzio della legge, all'applicazione dei principi generali in tema di esercizio dei diritti amministrativi nell'ambito degli enti collettivi: sarà dunque necessario porre i partecipanti nelle condizioni ottimali per l'esercizio consapevole del diritto di voto, sia per quel che concerne il procedimento da seguire sia, soprattutto, con riferimento alla materia oggetto della deliberazione, il cui ambito dovrà essere circoscritto a quanto espresso nell'ordine del giorno.

h) L'organo amministrativo.

Per quanto attiene alla nomina, cessazione e ai poteri degli amministratori, il regolamento prevede: *a*) che tali elementi debbano essere adeguatamente pubblicizzati con il deposito presso il registro dove viene iscritto il GEIE (art. 7); *b*) che la nomina degli amministratori possa essere effettuata sia nel contratto di gruppo sia, successivamente, con decisione dei membri (art. 19); *c*) che le condizioni di nomina e di revoca degli amministratori siano fissate nel contratto di gruppo; che la rappresentanza del gruppo spetti soltanto all'amministratore o agli amministratori (art. 20); *d*) che ciascuno degli amministratori, quando agisce a nome del gruppo, impegni il gruppo nei confronti dei terzi, anche se i suoi atti non rientrano nell'oggetto del gruppo, a meno che il gruppo stesso non provi che il terzo sapeva o non poteva ignorare, tenuto conto delle circostanze, che l'atto superava i limiti dell'oggetto del gruppo; *e*) che qualsiasi limitazione apportata dal contratto di gruppo o da una decisione dei membri ai poteri dell'amministratore o degli amministratori è inopponibile ai terzi anche se è stata pubblicata.

Si tratta, dunque, di norme molto rigide nella tutela dell'affidamento dei terzi. Rispetto a quelle analoghe che disciplinano i rapporti dei terzi con le società per azioni, queste norme pongono come criterio per decidere della rilevanza dell'estraneità dell'oggetto sociale non la "buona fede" del terzo, ma la conoscenza o conoscibilità della situazione da parte sua, "tenuto conto delle circostanze" (il Regolamento precisa che la sola pubblicazione dell'oggetto del gruppo non è sufficiente a costituire prova della conoscibilità). La differenza, in concreto, è quella che corre tra buona fede soggettiva e buona fede oggettiva.

Ad integrare la disciplina comunitaria sul punto è intervenuto il legislatore italiano affermando la possibilità che venga nominato amministratore anche una persona giuridica, la quale esercita le proprie funzioni attraverso un rappresentante da essa designato. Quest'ultimo assume chiaramente gli stessi obblighi e le stesse responsabilità civili e penali previste a carico degli amministratori persone fisiche, ferma restando la responsabilità solidale della persona giuridica amministratore (art. 5). Tale persona giuridica potrà essere anche un non-membro del GEIE: si apre quindi la strada per l'affidamento della gestione del GEIE a società di consulenza specializzate.

Per quel che concerne la responsabilità degli amministratori, nel silenzio della legge e del regolamento, dovrebbero valere (almeno per i GEIE italiani) la disciplina sul mandato ed il principio di solidarietà in caso di pluralità di amministratori (artt. 2608, sui consorzi e 2392, azione sociale di responsabilità nelle s.p.a., c.c.). Dovrebbero poi essere applicabili in via analogica gli artt. 2392 e 2393 c.c. sull'azione sociale di responsabilità, mentre inapplicabile dovrebbe essere l'art. 2394, sull'azione di responsabilità esercitata dai creditori sociali, tenuto conto del diverso ruolo che il patrimonio sociale assume nel GEIE, dove addirittura possono mancare i conferimenti e i membri rispondono illimitatamente per le obbligazioni assunte dal gruppo, rispetto alle società di capitali.

i) *Il regime della responsabilità del GEIE.*

Un aspetto particolarmente importante nell'ambito della disciplina del GEIE è quello costituito dal regime della responsabilità per le obbligazioni dallo stesso assunte. **Sul punto è utile porre a confronto la disciplina del GEIE con quella dei consorzi italiani, perché proprio su questo punto si registrano le differenze più rilevanti tra le due figure.**

Rispetto al consorzio, il GEIE è caratterizzato da una maggiore stabilità patrimoniale e gestoria, dalla inderogabile responsabilità illimitata e solidale dei suoi membri e quindi da una più ampia e sicura affidabilità sul mercato.

Come è noto il fondo consortile è costituito dai contributi dei consorziati e dai beni acquistati con essi (art. 2614 c.c.); ma l'entità dei contributi è rimessa alla libera determinazione dei consorziati medesimi. Il consorzio, dopo la novella del 1976, è caratterizzato dalla responsabilità limitata di tutti i suoi membri e dalla assenza di responsabilità delle persone che abbiano agito in nome del consorzio. La responsabilità illimitata del singolo consorziato è operante, secondo l'interpretazione data dalla giurisprudenza e dalla dottrina dominante, per le sole obbligazioni, per le quali il consorzio abbia positivamente fatto conoscere al terzo il nome del consorziato nel cui interesse l'operazione è compiuta.

Invece nel GEIE è bensì assente, sul piano giuridico, il conferimento e cioè un capitale destinato stabilmente all'esercizio dell'attività economico-produttiva, ma è presente la norma inderogabile per la quale i membri del gruppo debbano contribuire al saldo delle eccedenze delle uscite rispetto alle entrate nella proporzione prevista nel contratto di gruppo, o, in mancanza di questo, in parti uguali (art. 21, § 2 reg.). A questa più accentuata stabilità patrimoniale del GEIE si accompagna l'inderogabile responsabilità illimitata e solidale dei suoi membri (art. 24), solo in parte mitigata dalla espressa esclusione del fallimento dei membri del gruppo in conseguenza del fallimento del GEIE (art. 36 reg. e 9 d.lgs.).

La responsabilità dei membri è tuttavia *sussidiaria* rispetto a quella del GEIE: i creditori possono infatti agire nei confronti dei membri "soltanto dopo aver chiesto al gruppo di pagare e qualora il pagamento non sia stato effettuato entro un congruo termine". Non si tratta quindi di un vero e proprio beneficio di escussione, ma di un semplice onere di preventiva richiesta.

Ecco qui un altro fattore che potrebbe aver influito sullo scarso *appeal* in Italia dello strumento comunitario. La responsabilità illimitata dei membri del GEIE per le obbligazioni di qualsiasi natura da questo assunte fa sì che difficilmente lo stesso venga usato per lo svolgimento di attività associate costituite dal compimento di operazioni in nome del gruppo e nell'interesse solo di taluni dei membri dell'organizzazione. Infatti la responsabilità illimitata e solidale di tutti i membri del GEIE scatterebbe anche in conseguenza di tali operazioni sebbene l'attività comune sia stata, nel caso, realizzata nell'esclusivo interesse di un singolo. Ciò significa che il GEIE, particolarmente se operante in Italia, si orienterà solo allo svolgimento di operazioni nell'interesse comune di tutti i membri e quindi di interesse comune, pur se ausiliarie alle attività e alle economie di tutti i singoli associati, e non alla creazione di una organizzazione comune strumentale in modo differenziato alle singole attività economico-produttive, essendo per tale tipologia preferibile la disciplina italiana consortile sulla responsabilità.

Rispetto al caso che qui ne occupa, direi che la disciplina in punto di responsabilità personale dei singoli associati abbia un peso relativamente modesto: il "programma" di attività che si intende svolgere, infatti, sembra inidoneo ad esporre l'organizzazione ad obbligazioni di ammontare considerevole o, comunque, imprevedibili, come avverrebbe in caso di esercizio di attività di impresa in senso stretto.

l) Scioglimento e liquidazione del GEIE.

Nei considerando nn. 12 e 13 del regolamento si legge che "occorre prevedere e disciplinare le cause di scioglimento proprie del gruppo pur rinviando al diritto nazionale per la liquidazione e la chiusura di quest'ultima" e che "il gruppo è soggetto alle disposizioni del diritto nazionale che disciplinano l'insolvenza e la cessazione dei pagamenti e che tale diritto può prevedere altre cause di scioglimento del gruppo". Le fonti normative, per quanto concerne le cause di scioglimento, sono dunque sia nel regolamento sia nella legge nazionale.

La disciplina degli artt. 31 e 32 segnala rispettivamente cause di scioglimento a seguito di decisione dei membri oppure operative su pronuncia giudiziale.

Quanto alle prime (art. 31), da decidere all'unanimità salva diversa disposizione del contratto di gruppo o da pronunciare dal giudice su richiesta di qualsiasi membro se la decisione non è stata presa dopo tre mesi dal verificarsi delle medesime, rientrano:

- il decorso del termine;
- le cause previste dal contratto;
- la realizzazione dell'oggetto o l'impossibilità di conseguirlo.

Fra le seconde (art. 32), da pronunciarsi dal giudice a richiesta di ogni interessato o dall'autorità competente – con la possibilità di regolarizzazione della situazione viziata prima della decisione del giudice competente – si ricordano quelle conseguenti alla violazione degli artt. 3 (attività vietate al GEIE); 12 (criteri per l'individuazione della sede del gruppo) e 31, § 3 (mancanza delle condizioni di cui all'art. 4, § 3; ossia, il venir meno della transnazionalità).

A ciò va aggiunta la causa di scioglimento prevista dall'art. 9 d.lgs., ai sensi del quale il gruppo si scioglie in conseguenza della dichiarazione di fallimento dello stesso.

Lo scioglimento del gruppo comporta, ai sensi dell'art. 35 reg., la sua liquidazione. Non viene specificato se la fase di liquidazione subentra al verificarsi della causa di scioglimento o dal momento in cui la stessa viene accertata o dichiarata: sul punto va soltanto detto che, dopo la riforma del 2003, la causa di scioglimento ha effetto dal momento dell'iscrizione nel registro delle imprese della dichiarazione degli amministratori con la quale viene constato il verificarsi della causa di scioglimento.

Comunque, come anticipato, il regolamento rinvia in tema di liquidazione del GEIE alla disciplina nazionale: l'art. 8 d.lgs., dal canto suo, si limita a stabilire che la liquidazione del GEIE è regolata dagli artt. 2275 e ss. c.c., ossia dalle norme sulla liquidazione della società semplice, in quanto compatibili.

Sul punto, va osservato che il difficile rapporto tra interessi diversi che si realizza nella liquidazione delle società nel diritto italiano si complica nel caso del GEIE sia per la presenza di partecipanti al gruppo che hanno residenza o sede in paesi esteri, sia più in generale per l'ambito non nazionale di operatività e di rapporti del gruppo. Anche se, va detto, un qualche vantaggio in termini di semplificazione del compito da svolgere potrebbe derivare per i liquidatori del GEIE dallo scarso rilievo del momento patrimoniale del gruppo, il quale potrebbe finanche essere totalmente privo di capitale e dalla esistenza, anche in caso di GEIE con oggetto non commerciale, di scritture contabili e bilanci (art. 7, d.lgs.).

La chiusura della liquidazione deve essere pubblicizzata sulla G.U. e sulla G.U.C.E.. Nonostante la chiusura della liquidazione e la conseguente cancellazione dal registro delle imprese, permane la responsabilità illimitata dei partecipanti al gruppo per un termine di cinque anni dall'intervenuta pubblicazione.

A ciò va soltanto aggiunto che, vista la riforma della legge fallimentare, deve ritenersi che anche il GEIE sia sottoponibile al fallimento soltanto entro l'anno dall'intervenuta cancellazione dal registro (art. 10).

m) Sintesi.

Ricapitolando, e riprendendo i concetti espressi nella Relazione di accompagnamento del d.lgs. n. 240/1991, può dirsi che «il GEIE si colloca nell'area dei contratti di collaborazione piuttosto che in quelli di società, ovvero in quel campo (*joint-ventures*, associazioni temporanee, consorzi) in qualche modo intermedio tra l'esercizio dell'impresa in società e le mere forme di associazionismo non lucrativo; è deputato a fornire mezzi e strumenti di agevolazione, cooperazione, integrazione dell'attività economica dei soggetti partecipanti;

esso costituisce, sul piano delle finalità, un adeguato veicolo di espansione delle capacità economiche delle imprese sia sul piano comunitario sia rispetto alla concorrenza nei settori a tecnologia avanzata».

Come si è potuto constatare dalla sommaria esposizione della disciplina del GEIE, questo strumento di cooperazione presenta marcati aspetti di somiglianza con i consorzi con attività esterna (si pensi, su tutto, all'oggetto ed al fine del GEIE). Che la "*mutualità*" del GEIE, affermata anche da una delle rarissime pronunzie giurisprudenziali aventi ad oggetto il GEIE (Trib. Milano, 7 maggio 1992, in *Giur. it.*, 1993, I, 2, 192), sia sostanzialmente diversa da quella (generale) propria del fenomeno cooperativo e da quella (specifica) del fenomeno consortile lo si ricava anche dal fatto che nel GEIE manca la logica della "*porta aperta*"; l'ammissione di nuovi partecipanti richiede, infatti, l'unanimità dei consensi (art. 26 reg.) e potrebbe essere quindi resa impossibile anche dal dissenso di un singolo, mentre il recesso, in assenza di condizioni previste nel contratto di gruppo, può avere luogo solo per giusta causa o con l'accordo unanime degli altri membri (art. 27).

Non va poi dimenticato che alcune norme del regolamento traggono spunto dalla I direttiva in materia societaria (come ad esempio quelle, peraltro non del tutto coincidenti con gli artt. 2384 e 2384-*bis* c.c., sui poteri di rappresentanza e sui c.d. atti *ultra vires*; o quelle sugli effetti della dichiarazione di nullità del contratto), con conseguente avvicinamento della disciplina del GEIE a quella delle società di capitali.

Per altri versi ancora, la disciplina del GEIE pare modellata su quella delle società organizzate su base personale: si pensi, ad esempio, alle norme che prescrivono l'unanimità per alcune modifiche dell'atto costitutivo; o al rinvio, per la fase di liquidazione, alla disciplina propria della società semplice; o ancora al regime di responsabilità illimitata dei partecipanti per le obbligazioni del gruppo.

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CONCLUSIONI

Da quanto esposto, sembra possibile affermare che il modello organizzativo ed associativo più idoneo a realizzare le attività sopra indicate in relazione alla piattaforma software "icub" sia il GEIE: l'ampia autonomia lasciata alle parti nel plasmare le regole di funzionamento; l'inesistenza di un capitale minimo obbligatorio; le semplificazioni in ordine alla tenuta delle scritture contabili; la vocazione transnazionale e la matrice comunitaria dello stesso, fanno del GEIE un valido ed efficiente interlocutore delle Istituzioni europee, specialmente quando il "programma" dell'attività che si intende svolgere assume marcati connotati scientifici e di divulgazione culturale, non ancorato, cioè, alla logica del profitto e, dunque, non eccessivamente esposto al rischio imprenditoriale.

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In attesa di eventuali richieste di integrazioni e/o chiarimenti, invio i miei migliori saluti

Roma, 19 ottobre 2009

Prof. Avv. Daniele Vattermoli

Continuing (about the idea of forming a Consortium):

Con e-mail del 13 novembre 2009, il Prof. Giulio SANDINI, in nome e per conto della Fondazione dell'IIT (Italian Institute of Technology), richiedeva al sottoscritto la redazione di un parere *pro-veritate*, sulla base di una premessa e di quesiti qui di seguito, per comodità, riportati:

«PREMESSA

Con parere *pro-veritate* rassegnato sulla base di alcune indicazioni fornite dalla scrivente Fondazione con mail del 23.09.2009 si è individuata nella figura del GEIE la forma organizzativa ed associativa più opportuna per la costituzione di un soggetto giuridico attraverso il quale provvedere alla gestione della piattaforma software relativa al robot umanoide denominato "iCub". Il robot è il risultato del progetto europeo quinquennale "RobotCub", finanziato dalla Commissione Europea nell'ambito del Sesto Programma Quadro. RobotCub, che terminerà a gennaio 2010, è tuttora attuato da un consorzio di undici soggetti europei fra università, enti di ricerca ed industrie, sotto la guida di IIT che di fatto svolge il ruolo di leader di progetto. Nel corso della conference call del 02.11.2009, i responsabili del Dipartimento di Robotica, Scienze Cognitive e del Cervello (RBCS) della Fondazione hanno fornito una serie di nuovi elementi che di seguito di riportano per completezza:

1. l'organizzazione di cui sopra provvederà anche alla gestione della piattaforma hardware del robot, ovvero alla raccolta, selezione, armonizzazione, integrazione e ridistribuzione dei contributi ai disegni di progetto meccanico ed elettronico di iCub, che saranno realizzati da soggetti interni ed esterni all'organizzazione.

2. Sebbene si ritenga improbabile, non si può escludere che i contenuti delle piattaforme hardware e software, che sono e continueranno ad essere informazioni "open source" distribuite con licenza gpl o lgpl, possano violare diritti di privativa industriale di terzi. Questo rischio non è verosimilmente eliminabile poiché in futuro entrambe le piattaforme evolveranno continuamente, in seguito al contributo di un insieme numeroso di partner.

3. La Fondazione avrà un ruolo guida nell'organizzazione. IIT è il soggetto cardine dell'attuale consorzio RobotCub e possiede al suo interno il nucleo centrale della capacità scientifica e organizzativa necessaria alla realizzazione di iCub e dei suoi sviluppi futuri.

QUESITO

Poiché il Dipartimento di robotica ritiene verosimile che diversi soggetti (in particolare istituti universitari) che dovrebbero, fin dall'inizio, essere coinvolti nella costituzione del nuovo soggetto giuridico, potrebbero porre obiezioni in relazione all'utilizzo della figura del GEIE, soprattutto in considerazione della responsabilità illimitata e solidale dei raggruppati che dovrebbero garantire con il proprio patrimonio le obbligazioni assunte dal GEIE nei confronti di terzi.

Per tale ragione appare opportuno verificare la possibilità di provvedere alla gestione della piattaforma “iCub” attraverso un diverso soggetto giuridico che permetta agli associati di rispondere limitatamente alle somme conferite.

In tal senso si ritiene utile richiedere un ulteriore approfondimento che analizzi la possibilità di utilizzare per i fini descritti l’istituto contrattuale del consorzio.

Nell’ottica di predisporre una scheda informativa destinata ai diversi soggetti che dovrebbero essere potenzialmente coinvolti nella costituzione del soggetto giuridico cui demandare la gestione della piattaforma “iCub” si richiede un parere *pro-veritate* che fornisca:

1. un’analisi dei tratti maggiormente significativi della disciplina italiana del contratto di consorzio;

2. eventuali considerazioni circa l’opportunità di avvalersi di una tale figura giuridica per lo svolgimento delle attività necessarie alla gestione della piattaforma “iCub”».

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SOMMARIO: **1.** Il contratto di consorzio nell’ordinamento italiano. Premessa. – **1.1.** Segue. Costituzione: il contratto di consorzio e le sue modificazioni. – **1.2.** Segue. Il funzionamento del consorzio: organizzazione dei poteri e funzione esterna. – **1.3.** Segue. Regime patrimoniale e responsabilità. – **1.4.** Segue. Scioglimento. – **2.** Utilizzabilità dello strumento consortile per lo svolgimento delle attività necessarie alla gestione e allo sviluppo della piattaforma “iCub”. Evidenziazione dei problemi. – **2.1.** Segue. Possibili soluzioni. – **3.** Soluzioni alternative.

1. IL CONTRATTO DI CONSORZIO NELL’ORDINAMENTO ITALIANO. PREMESSA.

Il consorzio è un’associazione di persone fisiche o giuridiche, per la realizzazione in comune di un interesse proprio di queste persone. Con il consorzio non si crea artificiosamente una comunione di interessi che abbia una finalità sua propria, ma si realizza in comune un interesse che è già proprio di coloro che al consorzio partecipano: in definitiva, funzione del consorzio è essenzialmente quella di prestare un servizio nell’interesse dei singoli consorziati.

Secondo l’art. 2602 c.c. (come modificato dalla l. 10 maggio 1976, n. 377), «*con il contratto di consorzio due o più imprenditori istituiscono una organizzazione comune per la disciplina o per lo svolgimento di determinate fasi delle rispettive imprese*».

Sono *tre*, dunque, gli elementi che caratterizzano la figura del consorzio:

- la *natura contrattuale* dell’accordo;

- la creazione di *un’organizzazione comune*;

- la *finalità anticoncorrenziale* (**consorzio anticoncorrenziale**) e/o di *cooperazione interaziendale* (**consorzio di coordinamento**), realizzata attraverso un meccanismo non dissimile da quello mutualistico.

In via del tutto generale, va detto che il contratto consortile (contratto plurilaterale riconducibile alla categoria dei contratti associativi, in quanto caratterizzato dallo svolgimento di un'*attività comune*) è uno strumento pensato e disciplinato in un'ottica prettamente *imprenditoriale*: i partecipanti al consorzio, di norma, sono soggetti che svolgono professionalmente un'attività economica organizzata al fine della produzione e/o dello scambio di beni o di servizi – secondo la definizione di imprenditore offerta dall'art. 2082 c.c. – ed il consorzio (almeno nella sua variante di consorzio di coordinamento, che è quella che qui più interessa), quale forma di associazionismo tra imprenditori, viene da essi utilizzato per lo svolgimento più efficiente di determinate fasi di tale attività economica. Non a caso, come si è visto, nella nozione di consorzio di cui all'art. 2602 c.c., viene fatto espresso riferimento al *requisito soggettivo* di partecipazione al contratto consortile, nel senso che lo stesso è stipulato da «…due o più *imprenditori*…per lo svolgimento di determinate fasi delle rispettive *imprese*».

Il consorzio può atteggiarsi come mero intermediario (nel qual caso agendo come mandatario) delle imprese consorziate, oppure svolgere in proprio talune fasi delle imprese esercitate – fuori dal consorzio – dai consorziati: in quest'ultimo caso, è lo stesso consorzio che può assumere la qualifica di imprenditore (se ricorrono i presupposti di cui all'art. 2082 c.c.) e, nel caso svolgesse attività commerciale, restare soggetto alla disciplina del fallimento e delle altre procedure concorsuali (sul punto v. *infra*, § **2.1**). Ed è per questo che, nel caso in cui il consorzio sia dotato di un proprio ufficio destinato a svolgere un'attività con i terzi (sul punto v. *infra*, § **1.2**), è previsto l'obbligo di deposito del contratto presso il registro delle imprese (art. 2612 c.c.).

1.1. SEGUE. COSTITUZIONE: IL CONTRATTO DI CONSORZIO E LE SUE MODIFICAZIONI.

Il contratto di consorzio, ai sensi dell'art. 2603 c.c., deve essere fatto per *iscritto* sotto pena di *nullità* e deve indicare:

a) l'oggetto e la durata del consorzio, se quest'ultima è indeterminata, esso si deve intendere stipulato per un decennio (art. 2604 c.c.); il contratto può essere prorogato prima della scadenza del termine, ma è necessario il consenso di tutti i consorziati;

b) la sede dell'ufficio eventualmente costituito;

c) gli obblighi assunti e i contributi dovuti dai consorziati;

d) le attribuzioni e i poteri degli organi consortili anche in ordine alla rappresentanza in giudizio (sul punto mi soffermerò *infra*, § **1.2**);

e) le condizioni di ammissione di nuovi consorziati: la partecipazione di nuovi consorziati in tanto è ammissibile in quanto il contratto la preveda e in questo caso il contratto precisa i requisiti soggettivi ed oggettivi della partecipazione;

f) i casi di esclusione e di recesso: in mancanza di opportuna indicazione nel contratto, il singolo consorziato non potrà recedere *ad libitum*, né gli organi del consorzio potranno deliberare l'esclusione del consorziato;

g) le sanzioni per l'inadempimento degli obblighi dei consorziati (si tratta di una forma di penale);

h) le quote dei singoli consorziati o i criteri per la determinazione di esse (disposizione non rilevante, nel caso che qui ne occupa, in quanto applicabile nell'ipotesi in cui il consorzio abbia per oggetto il contingentamento della produzione o degli scambi).

Le modificazioni del contratto debbono essere fatte anch'esse per iscritto sotto pena di nullità (art. 2607, co. 2 c.c.). Esula dalla competenza degli organi consortili ogni modificazione del contratto originario, essendo espressamente ribadito in tema di consorzi il principio generale in tema di contratti, per cui la modificazione è possibile soltanto con il consenso di tutti i consorziati (con l'unica eccezione della trasformazione in società di capitali, che è assunta dalla maggioranza assoluta dei consorziati: art. 2500-*octies*, co. 2 c.c.). Peraltro, l'art. 2607, co. 1 prevede che il contratto possa anche disporre diversamente: così, ad esempio, potrà essere demandato all'assemblea dei consorziati di apportare modificazioni al contratto con deliberazione a maggioranza semplice o qualificata (salvo, è da ritenere, che la modificazione incida sugli obblighi originariamente assunti da un consorziato, nel qual caso sarà comunque necessario il consenso di quest'ultimo).

1.2. SEGUE. IL FUNZIONAMENTO DEL CONSORZIO: ORGANIZZAZIONE DEI POTERI E FUNZIONE ESTERNA.

A. La legge non precisa quali siano gli organismi consortili e quali le loro attribuzioni, L'organizzazione e la sua complessità rimangono quindi essenzialmente rimesse alla volontà dei consorziati manifestata nel contratto. Tuttavia la legge prevede che le deliberazioni relative all'attuazione dell'oggetto del consorzio siano prese con il voto favorevole della maggioranza dei consorziati, ove il contratto non disponga diversamente (art. 2606, co. 1 c.c.) e che, come anticipato, la deliberazione di trasformazione in società di capitali sia assunta con il voto favorevole della maggioranza assoluta dei consorziati (art. 2500-*octies*, co. 2 c.c.); con il che implicitamente si prevede come organo del consorzio l'*assemblea dei consorziati*. Nulla, peraltro, è detto a proposito delle modalità di computo delle maggioranze e delle regole di funzionamento dell'assemblea. Sembra tuttavia plausibile affermare che, in mancanza di diverse disposizioni contrattuali, le maggioranze devono essere calcolate per teste e le regole procedurali sono quelle che generalmente governano ogni organo collegiale (convocazione, adunanza, discussione e votazione).

Accanto all'assemblea, possono (anzi *debbono*, in caso di consorzi con attività esterna: v. *infra*, lett. *B*) essere nominati nel contratto *organi amministrativi* e *di controllo*, come si evince anche dall'art. 2605 c.c. («*i consorziati devono consentire i controlli e le ispezioni da parte degli organi previsti dal contratto*…»), ai quali siano rimesse l'esecuzione delle deliberazioni consortili e la vigilanza sull'esatto adempimento delle obbligazioni assunte.

Anche le attribuzioni e i poteri dei singoli organi possono essere liberamente modellati nel contratto: tuttavia, i poteri degli organi consortili riguardano essenzialmente l'attuazione dell'oggetto del contratto e trovano pertanto un limite insuperabile alla loro attività nell'ordinamento fissato nel contratto.

B. Il funzionamento e l'organizzazione del consorzio risultano notevolmente influenzati dal fatto che lo stesso sia meramente *interno* (ossia svolga una funzione riguardante unicamente i rapporti tra consorziati, coordinando l'azione dei singoli partecipanti attraverso la fissazione di direttive vincolanti per questi ultimi), oppure sia con *attività esterna*, ovvero sia dotato di un ufficio destinato a svolgere un'attività con i terzi (ed è il caso che qui specificamente interessa).

Lo svolgimento di un'attività con i terzi pone infatti un duplice ordine di esigenze: *a*) quello di far conoscere ai terzi che trattano con il consorzio tutti gli elementi necessari per il regolare svolgimento della loro attività con il consorzio; *b*) quello di attribuire al consorzio un'autonomia patrimoniale, in modo che i terzi abbiano un fondo sul quale soddisfarsi per le obbligazioni assunte dal consorzio (su questo specifico punto tornerò *infra*, § **1.3**).

La prima esigenza è soddisfatta – come si è anticipato – attraverso l'imposizione dell'obbligo di deposito di un estratto del contratto presso il registro delle imprese (art. 2612, co. 1 e 2 c.c.). Deposito al quale debbono provvedere, entro trenta giorni dalla stipulazione del contratto, gli *amministratori* del consorzio. E' dunque implicitamente richiesta la figura dell'amministratore: d'altra parte, l'art. 2613 c.c., nel disciplinare la rappresentanza in giudizio del consorzio, stabilisce che questa è attribuita *ex lege* al *presidente* del consorzio o a chi lo *dirige*, anche qualora la rappresentanza sostanziale sia attribuita ad altri.

Infine, dato che, ai sensi dell'art. 2615-*bis* c.c., chi dirige il consorzio è tenuto a predisporre, entro due mesi dalla chiusura dell'esercizio, una situazione patrimoniale osservando le norme relative al bilancio di esercizio delle società per azioni (da depositare, poi, presso il registro delle imprese) è da ritenere necessaria anche la nomina di un *organo di controllo* (quantomeno contabile) sull'operato degli amministratori.

1.3. SEGUE. REGIME PATRIMONIALE E RESPONSABILITÀ.

A. La seconda esigenza imposta dalla istituzione di un ufficio destinato a svolgere un'attività con i terzi, ossia quella di attribuire al consorzio un'autonomia patrimoniale per le obbligazioni dallo stesso assunte, viene soddisfatta attraverso la previsione di un fondo consortile (art. 2614 c.c.), costituito con i contributi dei consorziati e con i beni acquistati con detti contributi, che è indisponibile da parte dei singoli consorziati per tutta la durata del consorzio: in tal modo il fondo viene sottratto all'azione dei creditori particolari dei consorziati.

Naturalmente, nel fondo consortile potranno affluire sia eventuali lasciti, donazioni ed attribuzioni, a favore del consorzio, per atto tra vivi o *mortis causa*; sia le eventuali quote annuali per la gestione richieste ai consorziati; sia eventuali contribuzioni e sovvenzioni provenienti da Enti pubblici e privati; e sia, infine, i proventi delle iniziative intraprese dal consorzio.

B. Il fondo consortile è destinato a garanzia delle obbligazioni assunte dal consorzio e costituisce la sola garanzia per i creditori di questo (art. 2615, co. 1 c.c.). Il consorzio con attività esterna, in altri termini, pur essendo sfornito di personalità giuridica, è pur sempre un autonomo centro di rapporti giuridici e pertanto assume la responsabilità, garantita dal fondo consortile, per tutte le obbligazioni comunque derivanti dai contratti che stipula in nome proprio. Il consorzio, inoltre, risponde sia a titolo di responsabilità contrattuale, sia a titolo di responsabilità extracontrattuale, per fatto illecito.

Peraltro, la giurisprudenza ritiene che il consorzio possa rispondere, con il fondo consortile, dell'attività illecita posta in essere non solo dagli organi dello stesso, ma anche dalle singole consorziate. Così, ad esempio, Cass., 3 luglio 2008, n. 18235, ha affermato che se un terzo subisce un danno ingiusto provocato dall'esecuzione, da parte di una impresa consorziata, di opere o servizi oggetto di un contratto di appalto stipulato da un consorzio, è pur sempre questo ultimo a doverne rispondere, a titolo di responsabilità extracontrattuale, sotto il profilo del rischio derivante dalla gestione di una attività imprenditoriale.

L'autonomia patrimoniale perfetta del consorzio – rispetto ai patrimoni dei singoli consorziati –, che sembrerebbe discendere dalla lettura del co. 1 dell'art. 2615 c.c., subisce un temperamento nell'ipotesi in cui gli organi del consorzio abbiano assunto delle obbligazioni per conto esclusivo di singoli consorziati: in applicazione dei principi generali, l'agire per conto dovrebbe importare responsabilità del consorzio e inammissibilità da parte del terzo contraente di agire nei confronti dell'interessato (art. 1705 c.c.). Ma, in tema di consorzio, si deroga alla disciplina generale, affermandosi nei confronti del terzo la responsabilità del singolo consorziato solidalmente con il fondo consortile e stabilendosi, per il caso di insolvenza del consorziato obbligato, la ripartizione del debito dell'insolvente tra tutti i consorziati in proporzione della quota (art. 2615, co. 2). L'art. 2615 co. 2 c.c., rende cioè responsabili (anche) i consorziati, nonostante la mancata spendita del loro nome, essendo sufficiente che le obbligazioni siano assunte nel loro interesse.

1.4. SEGUE. SCIOGLIMENTO

Il contratto di consorzio, come ogni altro contratto associativo, si scioglie, oltre che per volontà unanime dei contraenti e per il decorso del tempo previsto per la sua durata o per le altre cause previste nel contratto, per il conseguimento dell'oggetto o per la impossibilità di conseguirlo; per deliberazione dei consorziati, quando sussiste una giusta causa; per provvedimento dell'autorità governativa nei casi ammessi dalla legge (art. 2611 c.c.).

2. UTILIZZABILITÀ DELLO STRUMENTO CONSORTILE PER LO SVOLGIMENTO DELLE ATTIVITÀ NECESSARIE ALLA GESTIONE E ALLO SVILUPPO DELLA PIATTAFORMA "ICUB". EVIDENZIAZIONE DEI PROBLEMI.

A. Il problema più rilevante che pone l'utilizzabilità del contratto di consorzio – così come pensato nell'ordinamento italiano e la cui disciplina si è sin qui sinteticamente descritta – per lo svolgimento delle attività necessarie alla gestione della piattaforma "iCub" è quello concernente il requisito della "imprenditorialità" dei soggetti destinati a parteciparvi, nonché quello, strettamente connesso al primo, dell'astratta riconducibilità nell'alveo dell'attività di impresa del programma di sviluppo e gestione della piattaforma "iCub".

Dai dati e dalle informazioni a mia disposizione sembrerebbe, invero, che, eccezion fatta per le industrie, i partners del nuovo soggetto che si intende costituire (ossia università e centri di ricerca) non possano essere considerati imprenditori ai sensi dell'art. 2082 c.c.; e, soprattutto, non lo siano con riferimento specifico al progetto "iCub". Il che, come si diceva, potrebbe rappresentare un ostacolo alla concreta utilizzabilità del contratto di consorzio nel caso di specie.

In precedenza si è detto, infatti, come il consorzio con attività esterna (il solo che qui interessa) possa anche non svolgere in proprio attività di impresa (non essere, cioè, esso stesso imprenditore), potendo il suo oggetto essere limitato, ad esempio, alla creazione di occasioni di lavoro e/o di risparmi di spesa direttamente a favore dei consorziati: invero, la causa del contratto di consorzio, dopo la modifica dell'art. 2602 c.c. apportata dalla l. n. 377/1976 (e, successivamente, dalla l. n. 240/1981), non è più limitata alla disciplina della concorrenza tra imprenditori esercenti una medesima attività economica o attività economiche connesse, ma ha un ambito più vasto grazie al quale il contratto stesso si rivela concepito quale strumento di collaborazione generale tra imprese diverse volto a realizzare le più razionali ed opportune sinergie. E' dunque ben possibile che l'attività del consorzio si ponga in funzione ausiliaria a quella svolta dai singoli consorziati, ma sempre nel presupposto che questi ultimi siano imprenditori e che, dunque, l'attività del consorzio sia di ausilio, appunto, ad un'attività di impresa.

Orbene, la gestione e lo sviluppo della piattaforma "iCub" – che dovrebbe rappresentare l'oggetto del futuro consorzio che si intende costituire – sembrerebbe attività che, per un verso, non è di ausilio alle imprese esercitate dai "futuri" consorziati (che, per quanto detto, non sono imprenditori) e, per altro verso, non integra essa stessa attività di impresa.

Su quest'ultimo aspetto va precisato che nella specie sembrerebbe difettare, su tutti, il requisito della *economicità*. Tale requisito va inteso nel senso che l'attività deve essere svolta secondo criteri tali da coprire i costi con i ricavi, secondo criteri, appunto, di obiettiva economicità. Questo significa che non è impresa l'organismo che produce beni o servizi erogandoli poi gratuitamente o a prezzi politici (la differenza può facilmente cogliersi confrontando l'ospedale, che non svolge attività di impresa, con la clinica privata, che invece va senz'altro qualificata come attività di impresa). L'economicità, d'altra parte, non va confusa con lo *scopo di lucro*: è irrilevante lo scopo soggettivo dell'imprenditore (che quindi può avere di mira i fini più diversi: lucrativi, genericamente egoistici, altruistici), quello che conta è l'obiettiva economicità dell'attività, cioè la sua idoneità a realizzare quanto meno la copertura dei costi con i ricavi (ciò spiega perché rientrano nel campo dell'impresa, ad esempio, sia le società cooperative sia gli enti pubblici economici).

Nel caso che qui ne occupa, la gestione e lo sviluppo della piattaforma "iCub" sembrerebbero essere orientate esclusivamente ad un accesso libero – ossia gratuito – delle varie e future applicazioni del Robot: ciò che, nell'ottica che qui più immediatamente interessa, esclude *a priori* – in quanto priva di corrispettivo – l'economicità della futura attività svolta dal consorzio.

B. A questo punto vale la pena soffermare l'attenzione sul rischio che potrebbe gravare sull'IIT e sugli altri partners del progetto, nell'eventualità in cui si voglia utilizzare in modo "anomalo" – ossia, slegato dall'ambito imprenditoriale – lo strumento consortile.

Quanto sin qui esposto non impedisce alle parti di stipulare un contratto denominandolo "consorzio"; né è ad esse impedito far riferimento, nello statuto di tale "consorzio", alle norme del codice civile che disciplinano tale istituto, al fine di modellare la "struttura" dell'organizzazione comune che attraverso tale contratto si intende costituire. Ciò che va sottolineato è che né il *nomen iuris* utilizzato né la struttura adottata possono "attribuire" la qualificazione giuridica di consorzio ad una organizzazione che di quest'ultimo non ne abbia i requisiti previsti dalla legge. Con la conseguenza, allora, che nel caso in cui un soggetto (ad esempio, un creditore) volesse far valere la vera natura giuridica di tale organizzazione (ad esempio, per far valere la responsabilità illimitata dei membri dell'organizzazione), ben potrebbe il giudice *riqualificare* tale consorzio in altro Ente, di cui il contratto istitutivo contiene tutti i requisiti previsti dalla legge; nel nostro caso, tale Ente altro non sarebbe se non l'*associazione non riconosciuta* (la cui disciplina è contenuta negli artt. 36 ss. c.c.), i cui tratti caratteristici sono, appunto, la pluralità degli associati; lo scopo ideale o altruistico; la tendenziale estraneità al mondo imprenditoriale. Dal che discenderebbe, secondo quanto stabilito dall'art. 36 c.c., che «*per le obbligazioni assunte dalle persone che rappresentano l'associazione i terzi possono far valere i loro diritti sul fondo comune. Delle obbligazioni stesse rispondono anche personalmente e solidalmente le persone che hanno agito in nome e per conto dell'associazione*».

2.1. SEGUE. POSSIBILI SOLUZIONI.

Come detto, il fenomeno consortile (almeno quello "tipico", la cui disciplina è contenuta negli articoli 2062 ss., c.c.) si innesta naturalmente nel mondo imprenditoriale: ed è proprio per tale intrinseca caratteristica che la sua utilizzabilità, nel caso che qui ne occupa, desta qualche perplessità. Il problema potrebbe però essere aggirato adottando degli accorgimenti che consentano al nuovo soggetto che si intende costituire di presentare tutti i requisiti previsti dall'art. 2062 c.c.

A. Si è già visto come nella nozione di consorzio *ex* art. 2062 c.c. si faccia riferimento agli imprenditori e alle imprese da essi esercitate: ciò premesso, non sembra tuttavia che l'espressione contenuta nella norma testé menzionata debba intendersi nel senso di porre un vincolo rigido in ordine alla tipologia dei soggetti che possono aderire al consorzio.

Non sembra, cioè, malgrado l'opinione contraria di parte minoritaria della dottrina, che i consorziati debbano essere necessariamente tutti imprenditori; in altri termini, dovrebbe essere consentito che, ferma restando la necessaria presenza di più imprenditori, al consorzio aderiscano anche soggetti diversi, sempre che ciò non alteri la causa del contratto. Pienamente aderente alla configurazione causale tipica del consorzio, pertanto, è la figura del consorzio *misto* (con la partecipazione, ad esempio, di enti pubblici non economici, onlus, fondazioni, ecc.) – peraltro, sempre più presente nella pratica, con il nome di *consorzio pubblico/privato* – nel quale la struttura consortile è diretta a perseguire interessi più *generali*.

Per quanto sin qui esposto sarebbe dunque possibile che il costituendo soggetto destinato a gestire e sviluppare la piattaforma "iCub" assuma i caratteri del consorzio, sempreché nella compagine dei consorziati figurino almeno due imprenditori: la presenza di una pluralità di imprenditori sembra, in effetti, rispondere perfettamente al requisito soggettivo richiesto dall'art. 2062 c.c.

B. Resta ora il "problema", al primo strettamente connesso, dell'attività che dovrà svolgere il futuro consorzio. Orbene, premesso che questo dovrà necessariamente assumere obbligazioni nell'interesse collettivo di tutti gli enti partecipanti al consorzio – in caso contrario, infatti, qualora il consorzio assumesse un'obbligazione per conto (ossia nell'interesse) di una sola consorziata, quest'ultima risponderebbe illimitatamente con il proprio patrimonio (in solido con il fondo consortile) di tale obbligazione, *ex* art. 2615, co. 2, c.c. –, l'attività delineata nello statuto deve essere tale da rispondere al requisito della *economicità* (ossia – giova ribadirlo – tale da assicurare la tendenziale copertura dei costi con i ricavi generati dall'attività). **A tale fine, sarà sufficiente non specificare nello statuto che tutte le possibili applicazioni derivanti dalla gestione e dallo sviluppo della piattaforma "iCub" saranno offerte liberamente (ossia, gratuitamente) sul mercato.**

Ciò, ovviamente, non significa che, *in punto di fatto*, i diritti connessi alla piattaforma – e dei quali il consorzio dovrà curare la gestione – non possano essere ceduti senza alcun corrispettivo (e che tale *modus operandi* sia, sempre in punto di fatto, la regola): l'importante è solo che lo statuto non escluda *a priori* l'economicità dell'attività svolta dal consorzio. Così come non esclude che lo stesso consorzio specifichi, nello statuto, che lo stesso è "*senza fine di lucro*", attesa la differenza, sul piano pratico e concettuale, tra lo scopo di lucro e l'intrinseca economicità dell'attività svolta (sul punto v. *retro*, **§ 2**).

Naturalmente, la riconduzione del futuro consorzio nell'ambito imprenditoriale presenta anche dei potenziali rischi: primo fra tutti l'assoggettamento a fallimento (e alle altre procedure concorsuali). Qualora, infatti, l'attività posta in essere dal consorzio riunisca tutti i requisiti di cui all'art. 2082 c.c., lo stesso, in quanto svolgente attività di tipo commerciale, sarebbe, in caso di insolvenza (insufficienza del fondo consortile a soddisfare regolarmente le obbligazioni assunte dal consorzio) e di superamento delle soglie dimensionali di cui all'art. 1, co. 2 l.fall., sottoposto a fallimento. La procedura concorsuale, in questo caso, non si estenderebbe ai singoli partecipanti (e sui loro patrimoni), ma potrebbe avere ripercussioni negative su coloro che hanno gestito il consorzio (azioni civili di responsabilità; reati fallimentari). Il problema da ultimo evidenziato non si porrebbe qualora i "ricavi" generati dal consorzio siano inferiori a 200 mila euro annui; l'attivo investito sia inferiore a 300 mila euro e l'esposizioni debitoria complessiva sia inferiore a 500 mila euro (che rappresentano le soglie dimensionali previste, appunto, dall'art. 1, co. 2 l.fall.).

3. SOLUZIONI ALTERNATIVE.

Da ultimo, qualche considerazione in ordine alle possibili soluzioni alternative a quella, qui presa in considerazione, del consorzio.

La via per giungere ad una responsabilità limitata dei futuri *partners* dell'ente incaricato di gestire e sviluppare la piattaforma "iCub" è quella che porta all'*associazione riconosciuta* (artt. 14 ss. c.c.), i cui tratti caratteristici sembrano essere compatibili con il nuovo soggetto che si intende costituire.

Infatti. La partecipazione all'associazione non è soggetta a particolari requisiti (possono parteciparvi enti pubblici e privati, persone fisiche, imprenditori o non imprenditori, ecc.); l'associazione può o meno svolgere attività di impresa; lo scopo dalla stessa perseguito è altruistico (qualsiasi utile prodotto dall'attività associativa non può essere ripartito tra gli associati, ma destinato al conseguimento dei fini istituzionali oppure al rafforzamento dell'associazione stessa); il fondo patrimoniale non è predeterminato, dovendo solo essere adeguato alle finalità che intende perseguire l'associazione; delle obbligazioni contratte in nome e per conto dell'associazione risponde soltanto il patrimonio dell'ente che, in virtù del riconoscimento, acquista personalità giuridica (con conseguente autonomia patrimoniale perfetta).

Per conseguire il *riconoscimento* (la cui disciplina è contenuta nel d.P.R. n. 361/2000) è necessario che lo scopo dell'associazione sia definito e lecito, che, come detto, il patrimonio sia adeguato alle finalità che intende perseguire e che l'atto costitutivo e lo statuto contengano indicazioni precise in ordine alla denominazione, alla sede ed all'ordinamento interno; in particolare, nello statuto dovranno essere disciplinate le modalità di costituzione e di funzionamento degli organi ed indicati i poteri attribuiti ai loro componenti. Infine, dovranno essere disciplinate le modalità di estinzione dell'associazione e di devoluzione del patrimonio.

Il riconoscimento si ottiene presentando alla prefettura nella cui provincia è stabilita la sede dell'associazione apposita domanda sottoscritta dal fondatore o da coloro ai quali è conferita la rappresentanza, allegandovi copia autentica dell'atto costitutivo e dello statuto. E' inoltre necessario dimostrare la consistenza del patrimonio attraverso idonea documentazione da allegare alla domanda. Entro 120 gironi dalla presentazione della domanda, il prefetto, verificato il possesso dei su indicati requisiti, provvede all'iscrizione nel registro delle persone giuridiche istituito presso le prefetture.

Un possibile ostacolo, di tipo funzionale, è posto dall'art. 2 d.P.R. n. 361/2000, il quale richiede, ai fini di ogni modifica dell'atto costitutivo e dello statuto, il controllo del prefetto, così come previsto in sede di costituzione dell'ente.

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Nella speranza di aver risposto esaurientemente ai quesiti che mi sono stati posti e restando a Vostra completa disposizione per ogni chiarimento che si renda necessario, porgo i miei più cordiali saluti.

Roma, 20 novembre 2009

Prof. Avv. Daniele Vattermoli