Project IST-004370

RobotCub

Development of the iCub Cognitive Humanoid Robot

Instrument: Integrated Project
Thematic Priority: IST – Cognitive Systems

Final Activity Report

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1. Foreword

This is still a draft version of the final report which is going to be integrated and structured according to the guidelines at the end of the project.

2. Introduction

Robotics, by definition, takes inspiration from nature and the concept of humanoid is perhaps the best example. When we consider the possibility of creating an artefact that acts in the world, we face a preliminary and fundamental choice: efficiency (task-specific) versus biological compatibility (evolving and versatile). The first option leads to the realization of automatic systems, very fast and precise in their operations. Limitations of automatic systems are purely technological ones (e.g. miniaturization). The second option is what we consider to be a humanoid: a biological-like system which takes decisions and acts in the environment, which learns how to behave in new situations (adapts), which invents new solutions on the basis of the past experience. The fascinating aspect of the humanoid is the possibility to interact with it: to teach, to demonstrate, even to communicate. It should be stressed that the attempt to adopt the strategy of 'biological compatibility' does not represent an intellectual exercise but is prompted by the idea that a humanoid interacting with human beings must share with them representations, motor behaviours and perhaps, even kinematics and degrees of freedom.

To interact, a humanoid must first act (and not simply move), perceive, categorize and therefore, understand. These capabilities cannot arise from pre-compiled software routines. On the contrary, they realize themselves through an ontogenetic pathway, simulating what happens in developing infants. In other words, humanoids must act in the environment to know it. It should be stressed that 'to know the environment' does not mean to categorize an assembly of static structures and objects but requires, as an essential requisite, to understand the consequences of generated actions (e.g. a glass breaks when falls on the ground). During this knowledge acquisition, attempts and errors are fundamental because they increase the exploration field. This is the main difference between a humanoid and an automatic system: for the latter, errors are not allowed by definition.

The developmental process leading to a 'mature' humanoid requires a continuous study of its human counterpart. This study only partially overlaps with traditional neuroscience, because of its peculiar interdisciplinarity. In other words, the synergy between neuroscience (particularly neurophysiology) and robotics, gives origin to a new discipline in which bi-directional benefits are expected. In fact, this knowledge sharing will reward not only robotics: the developing (learning) humanoid will form a behaving model to test neuro-scientific hypotheses, by simplifying some extremely complex problems. Particularly, it will allow what is not conceivable in human neuroscience: to investigate the effects of experimental manipulations on developmental processes.

The RobotCub project goes in this uncharted territory.

3. Basic facts

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. 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 carried out by the partners is leading edge research. Together, these efforts have led to a considerable number of publications, a large visibility in media, on the internet but more importantly a huge visibility in the scientific community (Nosengo, 2009).

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 RobotCub deliverable 2.1 (Vernon et al., 2009) contains already a full-fledged program of empirical research that may keep scientists busy for many years to come.

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[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] iCUB stands for i-*Cognitive Universal Body* (or *"I"* as in *"I Robot"* and *cub* as in "*man-cub*" of the Jungle Book.

[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.

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 deliverable 2.1 (Vernon et al., 2009) (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).

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).

4. Goals

RobotCub started from the considerations that the construction of cognitive systems could not progress without a certain number of ingredients:

- The development of a sound formal understanding of cognition (Vernon, Metta, & Sandini, 2007);
- The study of natural cognition and particularly important, the study of the development of cognition (Sandini, Metta, & Konczak, 1997; von Hofsten, 2003);
- The study of action in humans by using neuroscience methods (Fadiga, Fogassi, Gallese, & Rizzolatti, 2000; von Hofsten, 2004);
- The physical instantiation of these models in a behaving humanoid robot (Metta, Sandini, & Konczak, 1999; Metta, Sandini, Natale, & Panerai, 2001).

Establishing this agenda for research in cognitive systems was basically the implementation plan of the RobotCub project.

Unfortunately, there are many valid and often opposing viewpoints on how cognition can be modelled and synthesized. In a recent paper by Vernon, Metta and Sandini (Vernon, Metta, & Sandini, 2007), cognition is generally defined as implying the ability to understand how things might possibly be, not just now but at some future time, and to take this into consideration when determining how to act. Remembering what happened at some point in the past helps in anticipating future events: using the past to predict the future (Berthoz, 2000) and then assimilating what does actually happen to adapt and improve the system's anticipatory ability in a virtuous cycle that is embedded in an on-going process of action and perception. Cognition breaks free of the present in a way that allows the system to act effectively, to adapt, and to improve. Vernon, Metta and Sandini categorize the study of cognitive systems in two broad classes following the cognitivist or the emergent approach. Clark (Clark, 2001) retraces a similar evolution of the philosophy of cognitive science and proposes a similar classification of the study of cognitive systems.

For a cognitivist, cognition is a type of computation defined on symbolic representations, and cognitive systems instantiate such representations physically as cognitive codes and … their behaviour is a causal consequence of operations carried out on these codes (Pylyshyn, 1984). Connectionist, dynamical, and enactive systems, grouped together under the general heading of emergent systems, argue against the information processing view, a view that sees cognition as symbolic, rational, encapsulated, structured, and algorithmic, and argue in favour of a position that treats cognition as emergent, self-organizing, and dynamical (Kelso, 1999; Thelen & Smith, 1998).

Also with respect to ontogenetic development, cognitivist and emergent approaches take different views; the differences are truly fundamental and extend to many aspects of the study of cognition as for example the role of embodiment, the representational framework, and the problem of semantic grounding. To the former, development is not a requirement since cognitivist systems use patterns of symbol tokens that refer to events in the external world. These are typically the descriptive product of a human designer, usually, but not necessarily, punctuate and local. Emergent systems representations are global system states encoded in the dynamic organization of the system's distributed network of components. The same assumptions apply to the study of biological cognition; cognitivism assumes that cognition is about symbol manipulation and that the important issues are how to find the rules that effect the reasoning on the symbols. Whereas cognitivist systems do not need to be embodied, emergent systems typically stress the role of embodiment and the physical instantiation plays a direct constitutive role in the cognitive process (Krichmar & Edelman, 2005).

Perhaps, one recurrent theme in all approaches is the need for embodiment: the instantiation of a physically-active agent that can explore and manipulate its environment in order to develop the ability to effect useful interaction and communication with others. Whilst some view embodiment as a helpful but not necessarily essential requirement of cognitive systems, most researchers now acknowledge that it has a key role to play in understanding the cognitive process: artificial systems with cognitive abilities cannot be studied only through simulations and virtual environments but require the use of "artificial bodies". These bodies need to be designed and built in order to test theories and achieve real scientific advancement.

Specifically, RobotCub takes an emergent approach, for which ontogenetic development is the only possible solution to the acquisition of epistemic knowledge (the system's representations), where cognition is self-organizing and dynamical and, how we will see later, where cognition corresponds to the acquisition (and development) of anticipatory abilities. We will take this approach also in interpreting cognition in biological systems.

In this context, our goal in Robot-cub was two-fold: (1) to create an open physical platform for embodied research that can be taken up and used by the research community at large to further their particular approach to the development of cognitive systems, and (2) to advance our understanding of several key issues in cognition by exploiting this platform in the investigation of several cognitive capabilities. It is worth stressing the fact that, (1) we started from scratch in designing a complex humanoid robot: in three and a half year the design stage was completed and the robot ready for duplication in hardware and software and, simultaneously, (2) we carried out leading edge research, by defining a paradigm for robotic implementations starting from a roadmap of human development, by studying the motor system and its development in humans, by transforming this knowledge into a Cognitive Architecture and attempting (it would be preposterous to claim that we have finished in this task) a large scale implementation of the architecture. It is to be noted also that the building of a community around this ideas is fundamental for the success of RobotCub and for its legacy after the end of the project.

Our approach is based on a well-specified programme of experimental research, drawing on our broad multidisciplinary backgrounds in human developmental psychology, physiology, cognitive robotics, mechatronics, and perceptual science. Significantly, the design of the iCub was informed by this research programme and, in turn, the iCub implementation was used in planning developmental or physiologycal experiments.

We approached this goal by building an embodied system able to learn: i) how to interact with the environment (mainly) by complex manipulation and through gesture production/interpretation; and ii) how to develop its perceptual, motor and communication capabilities for the purpose of performing goal directed manipulation tasks. The embodied cognitive system (the iCub) was shaped, physically and mentally, like a human child and designed as an "open system" to be shared by scientists as a common tool for addressing cognition and human-robot interaction. This objective was framed in such a way to design both the mindware and bodyware of the iCub with the goal of providing the scientific community with a set of physically instantiated tools indispensable to study cognition.

Summarizing the project's concepts in three words, they are: Cognition, Development, and Embodiment.

In addressing the grand challenge of cognition (and in setting the framework of this project), we believe that it is more constructive to formulate a research scenario that deals explicitly with different points of view, since as we briefly illustrated earlier the basic truth is that many positions are all perfectly tenable (and plenty of arguments have been exposed in supporting each of them – (Kelso, 1999; Maturana & Varela, 1998; Posner & Cohen, 1984; Thelen & Smith, 1998)). Starting from our "fixed points" – i.e. Development and Embodiment – we first show to what degree the goals of the project have been attained, and later motivate them with respect to the state-of-the-art.

The main project objectives were:

- **From a technological point of view, a professionally documented, reproducible open platform shaped like a child-humanoid.** The project documentation contains all the information required to build the full body (and/or a subset of it), to install and run the robot's mindware, and it is professionally maintained to include future updates as well as new contributed subparts (e.g. see http://www.robotcub.org for links to the main documentation or http://www.icub.org for a manual of the iCub). The drawings and the source code are available to scientists with a GPL (General Public License). Several prototypes are also maintained and accessible to scientists to evaluate the system's performance and to test its usability (at the Italian Institute of Technology in Genoa, but also across Europe in various institutions). We consider this platform an essential tool to address issues related to embodied cognition. As it will be illustrated later, we believed that such a tool did not exist prior to the construction of the iCub even considering the humanoid robotic products developed recently by Japanese companies (e.g. Sony, Honda, etc.). To enable the investigation of relevant cognitive aspects of manipulation the design was aimed at maximizing the number of degrees of freedom (DOF) of the upper part of the body (head, torso, arms, and hands). The lower body (legs) were initially designed to support crawling "on four legs" and sitting on the ground in a stable position (and smoothly transition from crawling to sitting autonomously). A recent study and consequent modification of the legs allows bipedal walking, although this is still theoretical since the control software has not been developed yet. IIT is also designing a mobile base (on wheels) for the iCub which will allow mobility and autonomy (on battery). Mobility, in general, whether on wheels or by crawling, allows the robot to explore the environment and to grasp and manipulate objects on the floor. The size of the iCub is that of a three-four years old and the total number of degrees of freedom for the upper body is 41 (7 for each arm, 9 for each hand, 6 for the head and 3 for the torso and spine). The sensory system includes vision (a binocular system), touch, audition and inertial sensors. Functionally the iCub can coordinate the movement of the eyes & hands, grasp and manipulate lightweight objects of reasonable size and appearance, crawl on four legs and sit (Metta, Sandini, Vernon, Natale, & Nori, 2008; Tsagarakis et al., 2007).

- **From the scientific point of view, the understanding through real-world implementation of exploratory and manipulation-based cognitive skills integrating perception, reasoning, representation, and learning.** Some of these skills were studied and implemented on the iCub operating in real-time on realistic test cases. Within the wider scope of cognition, RobotCub addresses the cognitive aspects of manipulation and gestures production/understanding. In general, we would like to understand how to model and synthesize cognitive (adaptive, anticipatory, interactive, goal-achieving, and social) capabilities, emulating how humans learn to use their hands and arms not just for manipulation but also to convey information, to express their emotional status, to interact socially, and even just for the pleasure of it like in dancing or in certain types of body exercise. Our research agenda starts from cognitive neuroscience research and proceeds by addressing, for example, the role of manipulation as a source of knowledge and new experience, as a way to communicate socially, as a tool to teach and learn, or as a means to explore and control the environment. We would like to stress here that collaboration between neuroscience, computer science, and robotics is truly intended as bi-directional. On one side, the iCub Cognitive Architecture is a system as much as possible "biologically oriented"[6]. On the other side, real biological systems were examined according to problems that we deemed important for elucidating the role of certain behaviours or brain regions in a larger picture of the brain. Examples of this research are:
    - Grasp unknown objects on the basis of their shape and position with one and two hands;
    - To assemble simple objects with “plugs”;
    - To coordinate the use of two hands (e.g. parts mating, handling of soft materials);
    - Visuo-haptic object recognition and multimodal property transfer;
    - Visual recognition of the body gestures of others;
    - Imitation of one and two-hand gestures;
    - Communication and interaction through body and hand gestures.

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[6] It is important to note that biological plausibility or similarity in the iCub is never intended as a faithful implementation of neural simulations to a very detailed level. We don’t think that this approach is worth given the available hardware. The digital computer is not the brain and it would be wasteful to try to use computers in this sense. On the other hand, the gross features of the architecture are biologically plausible by including attention, memory (procedural and declarative), reaching, grasping, action selection, and affective state.

Each bullet point implies both the implementation in the artefact and possibly biological exploration in living systems. The software arising from this activity (the mindware) is distributed following the open source GPL licensing scheme.

- A no less important scientific objective was the study (and partially the implementation in an embodied artificial system) of the initial period of human cognitive development. On the artificial side, it is our intention, in fact, not to try to pre-program the cognitive skills outlined earlier but, similarly to what happens in humans, to implement them into a system that can learn much like a human baby does. We understand aspects of human development and can make specific informed choices in building an artificial adaptable system. For example, developmental science now points out at how much action, perception and cognition are tightly coupled in development. This means that cognition cannot be studied without considering action and embodiment and how perception and cognition are intertwined into development (von Hofsten, 2004). Exemplar experimental scenarios are:
    - Discovering the action possibilities of the body: the so called body map;
    - Learning to control one's upper and lower body (crawling, bending the torso) to reach for targets;
    - Learning to reach static targets;
    - Learning to reach moving targets;
    - Learning to balance in order to perform stable object manipulations when crawling or sitting;
    - Discovering and representing the shape of objects;
    - Learning to recognize and track visually static and moving targets;
    - Discovering and representing object affordances (e.g. the use of "tools");
    - Recognizing manipulation abilities of others and relating those to one's own manipulation abilities;
    - Learning to interpret and predict the gestures of others;
    - Learning new motor skills and new object affordances by imitating manipulation tasks performed by others.
    - Learning what to imitate and when to imitate others' gestures.
    - Learning regulating interaction dynamics;

  Clearly, this is far from a completed endeavour, we have set the basis though for a solid development in this direction by providing the platform and by setting up the whole infrastructure (together with examples and large parts of this set of behaviours).

To achieve these goals it has been essential to address the relevant scientific problems from different perspectives and with different backgrounds. For this reason the project Consortium is multidisciplinary and includes laboratories and research centres specializing in Human Sensory and Cognitive Development, Neurophysiology, Cognitive Robotics, Artificial Intelligence and Computational and Cognitive Neuroscience. Starting from the initial group of partners, the RobotCub Consortium stimulated the formation of an international scientific community addressing aspects of embodied cognition. Further RobotCub launched an Open Call for proposals in using the iCub for cognitive systems research. We selected seven winners which were given a full iCub free of charge. Four additional platforms are available within the Consortium and more were eventually built when other projects and laboratories joined the challenge. We believe that the success of the open platform is also very much related to the diffusion (number of laboratories) that will adopt the iCub for their research agenda. Along this direction RobotCub has been successful in attracting interest (although the price is still a limiting factor to a wider diffusion).

The commonality between the RobotCub partners, the Open Call winners and others that have joined in is cognition and the interest in investigating the development of cognitive abilities in machines by, inter alia, expanding and exploiting our understanding of the development of human cognition.

Considering that one of the outcomes of iCub was to build a research tool in the form of a humanoid robot and the infrastructure to share/update it with other scientists interested in cognition and cognitive robotics, we had to design a robot as a whole with performance suited for Cognitive Systems research (as compared for instance with industrial robotics).

The reason why we believe that the strategy proposed in RobotCub of developing synergistically both the “body” and the “architecture” of the cognitive system, is the best solution with respect to others (such as modifying existing off-the-shelf systems), is threefold:

- **Unity of cognition:** since the goal is to study cognition, it has been necessary to design the “body” along with the “cognitive architecture” because the scientific questions we ask are likely to serve as guidelines for the design of the mechanical and electronic components. Vice versa only if the body has certain properties then it is possible to address the issues relevant to cognition. For example, a system that has to learn how to build a visuo-haptic representation of an object requires dexterous hands providing postural as well as haptic information with relatively high accuracy. Without such performance the cognitive goal would be meaningless (or it might prove not to be significant).
- **Exploiting holistic design:** a system of the required complexity in order to be realizable has to be designed as a whole. Only a few centres in the world have (or had) the resources to design whole-body humanoids (some of them are participating in this project) while most of the research centres interested in cognition have been bound to designing and implementing sub-parts (like heads or arms) relying on off-the-shelf components for the remaining parts. Both solutions are suboptimal. The first because the expertise required in building a whole-body device, is so wide that even in the most prestigious centres the outcome is, at best, a very complex masterpiece, draining a considerable amount of effort just for maintenance and marginal updates. The second because the off-the-shelf components usually constrain the overall performance by limiting the motor or sensory capabilities and by preventing the exploitation of mechanical, electrical or processing similarities between the sub-components. For example designing the arm and the hand together will allow choosing the best positioning of the actuators as well as the most appropriate transmission mechanism for each degree of freedom (gears, tendons, belts). The same would apply if jointly designing the head-shoulder and torso (since they share the same physical space).
- **Cost effectiveness:** designing complex systems is certainly an expensive exercise and without a joint effort, each research centre interested in cognition is bound to invest a considerable amount

of funds in this activity. This duplication of efforts limits the diffusion of such tools into the scientific community. It is also important to take into consideration that this investment is necessary yet not sufficient to investigate cognition and by itself does not contribute to the scientific advancement of the field. By actively and jointly participating to the design of the robot's body we expect a much larger acceptance of the device, a better focusing on the "real" problems of cognition and, consequently, a much higher cost-effectiveness ratio.

Particularly, in relation to the study of manipulation the commercially available humanoid systems are somehow limited and, in fact, the existing devices prevent addressing the important issues of manipulation for lack of motor and sensory skills. More specifically:

- No commercial device (not even the most sophisticated Japanese humanoids such as the Honda Asimo nor the Sony SDR) has arms and hands that can be used for skilled manipulation. Most of the current humanoids are very good at locomotion or whole-body gestures but rather limited for manipulation. Considering the importance of manipulation in the interaction with the environment and in the processes of learning by experimentation and imitation, we believe that a solution pursuing the use of an off-the-shelf device has inherent strong limitations preventing its use in addressing significant cognitive tasks.
- No commercial device has rich enough sensory capabilities to support the development of cognitive manipulation abilities. Touch sensors in the form of skin-like surfaces are not generally available and even torque sensing is at best limited to the lower limbs and used to balance during locomotion. Fitting existing systems with additional sensory systems (e.g. touch) is not a simple solution either because many of them are often proprietary architectures or they are likely to require drastic hardware modifications (e.g. in wiring the sensory system).
- Many existing systems are designed with a short demonstration or exhibition in mind rather than for continuous use such as that required in learning experiments. This poses constraints both in designing the body and the control structure. The robot should be reasonably safe since it cannot be closely monitored over such long periods of time.

The project workplan was particularly tight with about three years for designing the robotic platform including hardware and software. A substantial part of the budget (about 25%) was reserved for the Open Call (for the robot duplication) with the goal of including additional research into the project portfolio, via a competitive call having the goal of using the iCub to implement cognitive skills. RobotCub funds were also employed to build several copies of the iCub both for the Open Call and the Consortium. The Italian Institute of Technology (a late addition to the project) supported actions for hosting scientists to work on the iCub (the so called Research and Training Site) and the organization of the Summer School, an important yearly event where people spent ten full days using the robots and of generic training events (Winter School) on the iCub mechanics and electronics.

In summary, within RobotCub we addressed both theoretical questions on the modelling of cognition, on the relation between development and cognition, and more empirical ones on how a novel engineering practice might arise from taking into account developmental strategies/mechanisms. More importantly theory was grounded on a solid experimental interdisciplinary framework. We already motivated why building a platform is the best solution with respect to other solutions where an existing platform is taken up by the project.

An additional motivation resides in the fact that robotic manipulation abilities lag behind. Much of the existing research on humanoid robots even when motivated by cognition (this has not been always the case) has been missing “real” manipulation. It is not the case that manipulation has been completely neglected (e.g. industrial type manipulators) but rather that flexible, reliable, and general purpose manipulation has proved to be difficult involving perception, learning, reasoning, etc. A state-of-the-art robotic system can now reliably navigate in the environment, map it, get to interact primitively in it, touch/push things, but definitely it cannot really manipulate small objects, solve tasks according to the available objects, tools, etc., and communicate appropriately with people (besides speech synthesis). It is unfortunate since neural science tells us a story (a summary can be found in (Arbib, 2000)) where manipulation is central to human cognition. In fact, manipulation is the way through which we get to grips with the world, with the concept of objecthood, with the social environment, and further, if we subscribe to this story, communication to the level of language evolved out of a process of adaptation of the manual system into the one that controls speech. Not less important RobotCub has legs for crawling which gives the robot a chance for building its own experience by exploring the environment, fetching objects, etc. This raises a whole new set of issues since the robot has to link its perceptual abilities’ frame of reference to a moving environment rather than to the usual fixed one as in many stationary platforms. One example is in building the understanding of the limits of the robot’s own body: in this case, the robot can exploit the fact that its body is relatively constant over time while the environment has a higher variability. A high variability in the environment helps in building this important distinction. This later aspects have been only marginally addressed towards the end of the project.

Further, we believe that in investigating the construction of a cognitive system we cannot prescind from considering the study of the construction of natural cognitive systems: that is development. A successful cognitive architecture likely emerges from considering and investigating cognitive development. A possible outcome of this synergy between engineering and developmental sciences is the building of a novel set of methods for dealing with design problems at large: that is, how do we build complex, adaptable, interacting systems? We believe that this confrontation with developmental sciences is important and RobotCub sorts of paves the way to a new approach to cognitive systems.

5. Specific results

The RobotCub workplan was organized around a certain number of workpackages (WPs) which covered the foundations of human development (WP2), of sensorimotor coordination (WP3), of manipulation and affordances (WP4) and of imitation and communication (WP5N, formerly WP5 and WP6). From the technical point of view, mechantronics (WP7), software and documentation (WP8) were developed. Particularly important, given the open strategy of RobotCub, is also WP9 devoted in general to dissemination and community building activities.

Initially, modelling activities were led by the neuroscience partners, and are epitomized by the creation of a roadmap of human development (with application to the development of artificial cognitive systems). In parallel, the design of the humanoid robot started, standards were defined and progress was quick. Standards for software were also defined and these led to the adoption and redesign of the YARP open source library (in fact, developed by some of RobotCub people before the project). Year 3 and 4 were crucial for the iCub development, especially, year 4 saw the launch of the Open Call and consequently the realization of multiple copies of the iCub. Debugging was furious and RobotCub invested a huge effort in engineering activities. Simultaneously, a better formalization of the software development process happened in year 3 (in part by relying on YARP). It became also clearer what level of the Cognitive Architecture could possibly be implemented. These activities were carried out until the end of the project. Neuroscience continued to provide a reference and the basis to judge the more technical work. Perhaps, development and implementation did not happen as cleanly as possible but it is to be noted that RobotCub is, in many aspects, a research project with industrial requirements (in terms of mechanics, documentation, electronics, software development). It is to be expected that a Consortium made of Universities and research centres required time to get organized. Formal software and hardware development is not necessarily the primary goal of a research laboratory.

In the following, we summarize the main results of the various Workpackages, trying to cover some of the most exciting results of the project.

WP2, the roadmap of cognitive development

This Workpackage is about the study of 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.

WP2 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.

RobotCub takes an emergent approach to the study of cognition, for which ontogenetic development is the only possible solution to the acquisition of epistemic knowledge (the system's representations), where cognition is self-organizing and dynamical and, how we will see later, where cognition corresponds to the acquisition (and development) of anticipatory abilities. We take this approach also in interpreting cognition in biological systems.

Consequently, the next important question is about the principles that govern the ontogenetic development of biological organisms (e.g. as in (von Hofsten, 2004)). Converging evidence from various disciplines including developmental psychology and neuroscience is showing that behaviour in biological organisms is organized in primitives that we can call actions (as opposite to movements or reactions). Actions are behaviours initiated by a motivated subject, defined by goals and guided using prospective information (prediction). Elementary behaviours are thus not reflexes but actions with goals, where perception and movement are integrated, initiated because of a motivation and that are guided by and through prediction (von Hofsten, 2004).

To make this more operational and provide a description of human development, we have to consider three basic elements:

- What is innate, where do we start from?
- What drives development?
- How new knowledge is incorporated, i.e. what are the rules of development?

In looking at the first question, developmental psychologists, typically refer to innate elements in terms of prenatal prestructuring or the so-called core abilities. Neither is to be imagined like a rigid determination of perception-action couplings but rather means to facilitate development. Examples can be found in the prestructuring of the morphology of the body, in the perceptual and in the motor systems.

The motor system requires constraints in order to reduce the large number of effective degrees of freedom and these constraints come in the form of muscular synergies. That is, to facilitate control, the activation of muscles is therefore organized into functional synergies at the beginning of life (and they are probably formed already prenatally (de Vries, Visser, & Prechtl, 1982)). Similarly, perceptual structuring begins early in ontogenesis by relying on the interaction between genetic and self-activity factors (M.H. Johnson, 1997; Quartz & Sejnowski, 1997; von der Malsburg & Singer, 1988). Further to these, prestructuring comes also in the form of specific core abilities. Spelke (Spelke, 2000) is one of the proponents of this view. She discusses various aspects that show prestructuring, such as the perception of objects and the way they move, the perception of geometric relationships and numerosities, and the understanding of persons and their actions. An important part of the core knowledge has to do with people.

Knowing the initial "state" of the system is only the first step. A model of human development then requires establishing what causes it. Motivations come in different forms in the newborn: social and explorative. The social motive is what puts the infant in the broader context of other human beings, thus providing further possibilities for learning, safety, comfort, etc. Communication and language also develop within the context of social interaction (M. H. Johnson & Morton, 1991).

The third basic element of this summary of human development is to show how new knowledge is acquired and incorporated. The brain is only one side of this process, without interaction with the environment it would be of little use. Undoubtedly, the brain has its own dynamics (proliferation of neurons, maps formation, migration, etc.) but the “final product” is shaped by the dynamical interaction with the environment. Factors like exposure or deprivation to the environment, the body biomechanics and body growth are all fundamental to the development of cognition. For instance, the appearance of reaching depends critically on the appearance of 3D perception through binocular disparity, on the emergence of postural control (and muscle strength), on the separation of the extension-flexion synergies in the arm and hand, on the perception of external motion, control of the eyes for tracking and so forth. This is to say that no single factor determines the appearance of a particular new behaviour and it is therefore important to model complete systems in order to analyze even “relatively” simple cognitive behaviours.

Complementary to developmental studies, neurophysiology is also helping out to show the inextricably complexity of the brain. Tantalizing results from neuroscience are shedding light on the mixed motor and sensory representations used by the brain during reaching, grasping, and object manipulation. We now know a great deal about what happens in the brain during these activities, but not necessarily why. Is the integration we see functionally important, or just a reflection of evolution’s lack of enthusiasm for sharp modularity? A useful concept to understand how such capabilities could develop is the well-known theory of Ungerleider and Mishkin (Ungerleider & Mishkin, 1982) who first formulated the hypothesis that the brain’s visual pathways split into two main streams: the dorsal and the ventral. The dorsal is the so-called “where” pathway, concerned with the analysis of the spatial aspects of motor control. The ventral is related with the “what”, that is, the identity of the targets of action. Milner and Goodale (Milner & Goodale, 1995) refined the theory by proposing that objects are represented differently during action than they are for a purely perceptual task. The dorsal deals with the information required for action, whereas the ventral is important for more cognitive tasks such as maintaining an object’s identity and constancy. Although the dorsal/ventral segregation is emphasized by many commentators, it is significant that there is a great deal of cross talk between the streams (Jeannerod, 1997).

Among the arguments in favour of the ‘pragmatic’ role of the visual information processed in the dorsal stream, are the functional properties of the parieto-frontal circuits. For reason of space we cannot review here the functional properties of these circuits, e.g. that formed by area LIP and FEF, those constituted of parietal area VIP (ventral intraparietal) and frontal area F4 (ventral premotor cortex) or the pathway that connects area AIP (anterior intraparietal) with area F5 (dorsal premotor cortex). The same functional principle is valid, however, throughout these connections. Area F5, one of the main targets of the projection from AIP (to which it sends back recurrent connections), was thoroughly investigated by Rizzolatti and colleagues (Gallese, Fadiga, Fogassi, & Rizzolatti, 1996). F5 neurons can be classified in at least two different categories: canonical and mirror.

Canonical and mirror neurons are indistinguishable from each other on the basis of their motor responses; their visual responses, however, are quite different. The canonical type is active in two situations: (1) when grasping an object and (2) when fixating that same object. For example, a neuron active when grasping a ring also fires when the monkey simply looks at the ring. This could be thought of as a neural analogue of the "affordances" of Gibson (Gibson, 1977). The second type of neuron identified in F5, the mirror neuron (Fadiga, Fogassi, Gallese, & Rizzolatti, 2000), becomes active under either of two conditions: i) when manipulating an object (e.g. grasping it, as for canonical neurons), and ii) when watching someone else performing the same action on the same object. This is a more subtle representation of objects, which allows and supports, at least in theory, mimicry behaviours. In humans, area F5 is thought to correspond to Broca's area; there is an intriguing link between gesture understanding, language, imitation, and mirror neurons (Fadiga, Craighero, Buccino, & Rizzolatti, 2002; Rizzolatti & Arbib, 1998). The STS region and parts of TE contain neurons that are similar in response to mirror neurons (Perrett, Mistlin, Harries, & Chitty, 1990). They respond to the sight of the hand; the main difference compared to F5 is that they lack the motor response. It is likely that they participate in the processing of the visual information and then communicate with F5 (Gallese, Fadiga, Fogassi, & Rizzolatti, 1996), most likely via the parietal cortex.

Studying the motor system is consequently a complete activity involving sensorimotor loops which have a role in the recognition of objects (Sakata, Taira, Kusunoki, Murata, & Tanaka, 1997), of actions (Rizzolatti, Fadiga, Gallese, & Fogassi, 1996), in planning and understanding the intentions of others (Fogassi et al., 2005) as well as in language (D'Ausilio et al., 2009; Fadiga, Craighero, Buccino, & Rizzolatti, 2002). The involvement of the motor areas during observation of actions has been recently analyzed in human subjects using the H-reflex and TMS-evoked motor potentials (Borroni, Montagna, Cerri, & Baldissera, 2005; D'Ausilio et al., 2009). It has been shown that the so-called "motor resonance" phenomenon (Gallese, Fadiga, Fogassi, & Rizzolatti, 1996) is not relegated to the cortex but, rather, it spreads far deeper than initially thought. It has been shown that the spinal cord excitability is modulated selectively under threshold by the observation of others. In particular, in this experiment, the excitability of the spinal cord was assessed and it was determined to reflect an anticipatory pattern similar to the actual muscular activation with respect to the kinematics of the action.

These are only some of the experiments and studies supported by RobotCub in the context of WP2 (and later WP3). For detailed references and results, the reader is referred to deliverable 2.1 (Vernon et al., 2009) and the RobotCub website (http://www.robotcub.org). Further WP2 developed a Cognitive Architecture, based on the indications and models provided by neuroscientists. This architecture was initially loosely modelled after the "shared workspace architecture" of Shanahan (Shanahan, 2005) but later evolved into something different which is unique to RobotCub. WP2 also defined a set of scenarios and empirical tests of the Cognitive Architecture. For example, for looking:

> *Saccades and gaze redirection test*
> *A face pattern is introduced into the peripheral visual field (30° from the centre). The visual angle corresponds to that of a real face at 0.5m. When this happens, the iCub moves the eyes and head to position the face at the centre of the visual field. They both start at the same time, but the eyes arrive first to its new position. When the eyes are at the final position and the head moves there, the gaze stays at the fixation object while the eyes counter rotate until they look straight ahead again. The same thing should also happen when a colourful object (3°– 8° visual angle) is introduced into the visual field or when a sounding object is introduced to the side of the robot*

(30° – 50°). New objects that the robot has not seen before will attract the gaze more than familiar objects.

The main idea is to be able – once the Cognitive Architecture is completed – to test the iCub similarly to what a developmental psychologist would test an infant in a laboratory experiment.

WP3, sensorimotor coordination models

In Workpackage 3, we studied and modelled the development of sensorimotor coordination and sensorimotor mapping. We identified 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.

The postulate that action and perception are interwoven (see WP2) 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.

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.
- **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.
- **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.
- **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).

During the project the neuroscience partners were mainly involved in the investigation of sensorimotor representations and their role in cognitive functions. These results contributed to give an indication for the implementation of sensorimotor skills in the iCub, in order to allow a biologically plausible model for object interaction and others' action recognition. Multiple experimental techniques and approaches have been used to pursue this goal. In particular, RobotCub was involved in electrophysiological experiments on both humans and animals (transcranial magnetic stimulation, single neuron recordings), brain imaging experiments (functional magnetic resonance, near infrared spectroscopy), kinematics and gaze tracking recordings, behavioural experiments on both normal individuals and patients (autistic children and frontal aphasic patients). These contributions covered all the Workpackages further clarifying the strict interdependence between the motor command and the sensory consequences of action execution and its fundamental role in the building and development of cognitive functions.

For example, 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 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.

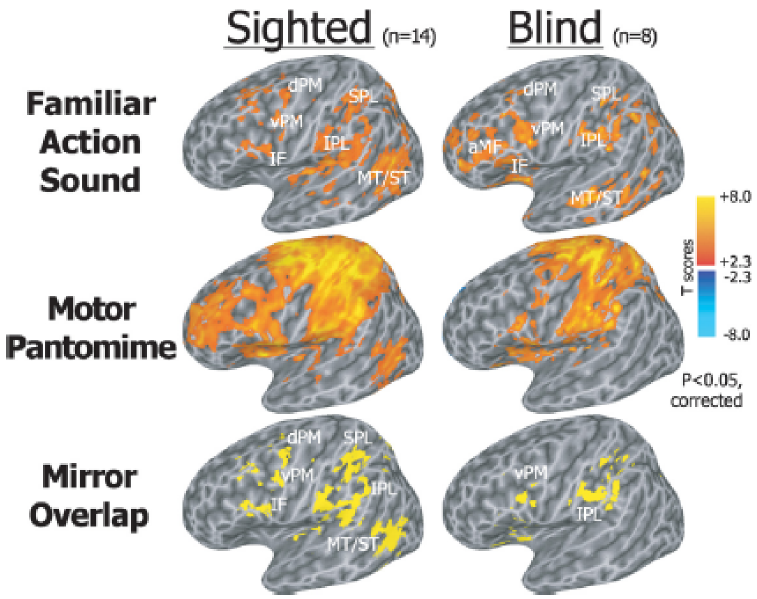


Figure 1: Statistical maps showing brain regions activated during listening to familiar action compared with environmental sounds, and during the motor pantomime of action compared with

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.

Along the same line of investigation, 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.

WP4, object affordances

The goal of this Workpackage was 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 were 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 investigated:

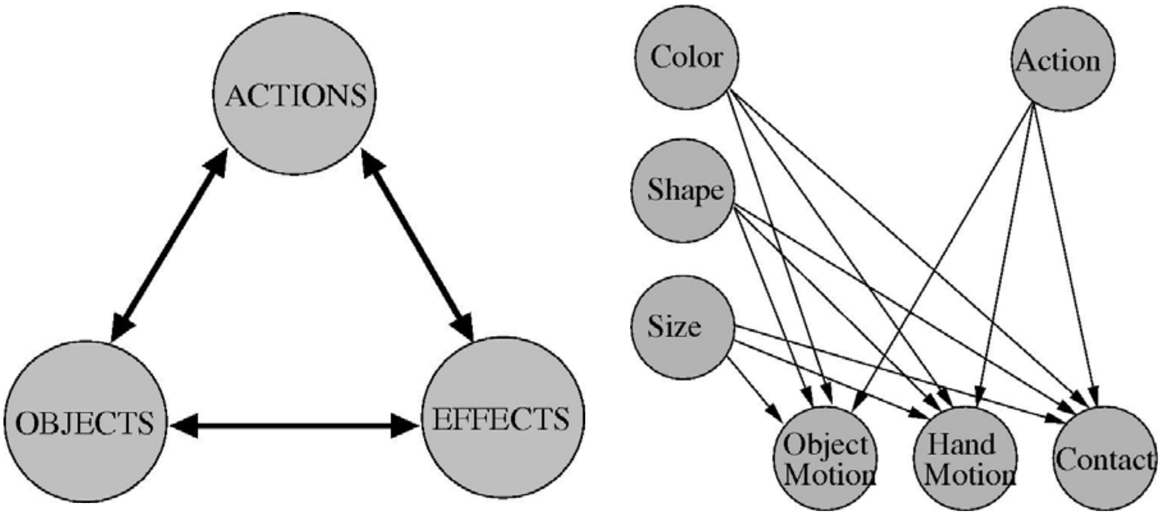
1. What exploratory behaviours support the acquisition of affordances, what is the relevant information (visual, haptic, motor, etc.)?
2. The development of a model of the acquisition of object affordances and how the motor information enters into the description of perceptual quantities.
3. In analogy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

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).

RobotCub introduced the idea of using Bayesian Networks (BN) to model the dependencies between robot actions, object characteristics and the resulting effects, therefore in practice modelling affordances along the way. Briefly, a BN is described by a set of nodes that represent random variables, a set of directed arcs that encode conditional dependencies and a set of conditional probability distributions. A BN encodes causality since an arc from a node X to a node Y can be interpreted as X causes Y. We assumed that the robot had developed certain skills prior to be able to learn affordance: a motor repertoire (A), perhaps derived from experience, an object feature repertoire (F) also potentially acquired via object manipulation and the effects (E) resulting from manipulating the environment.

The interaction of the iCub with the environment is therefore formalized in using one action *a* from A on certain objects with features F (or a subset of them) to obtain effects *e* from E. This information can be used to estimate the BN structure and parameters using different learning algorithms. These parameters can be updated online as the robot performs more experiments. Also, they can be updated by observation of other agents. Examples are shown in Figure 2



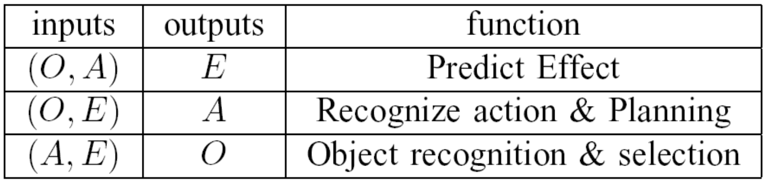
(a) (b)

Figure 2: (a) General affordance scheme relating actions, objects (through their characteristics) and the resulting effects. (b) A particular BN encoding affordances.

This model has some nice properties as for example:

- Affordance learning through self-experience;
- Feature selection (or detection of irrelevant features);
- Affordance learning through self-observation (restricted to the update of the probability distributions);
- Usage of the model to perform prediction, recognition and planning.

The use of the network is done based on probabilistic queries. These queries may take as input any combination of actions, objects and features and compute conditional distributions of one or more of the other variables. The following table summarizes some of the basic operations that can be performed with the network:



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

Table 1: Using affordances for prediction, recognition and planning.

Based on the previous model, we have performed several experiments with the robotic platform shown in Figure 3. We used a playground scenario consisting of several objects with two shapes (box and ball), different sizes and colours. The robot was able to perform three different actions: grasp, tap and touch.

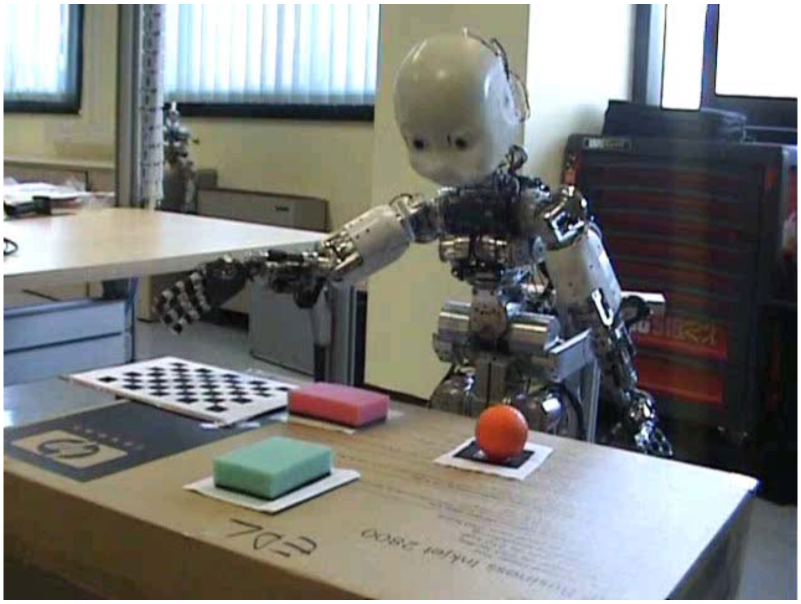


Figure 3: (a) The playground for the robot contains objects of several sizes, colours and shapes. Protocol: the object to interact with is selected manually, the action is random (from the set of actions A). Object properties are recorded when the hand is not occluding the object. The effects are recorded later and then the robot hand goes open loop to a resting position.

An example of an affordance network is:

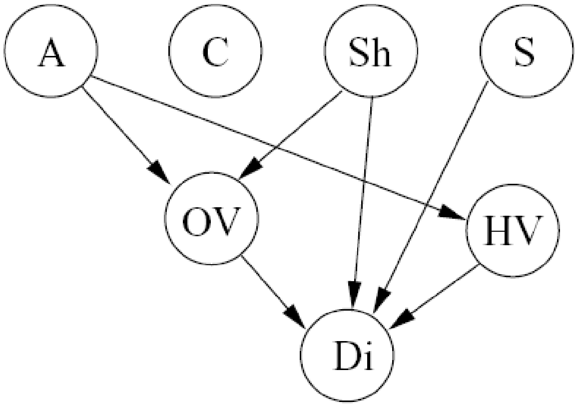


Figure 4: Learnt network. The variables represent A- Action, C- Object Colour, Sh- Object Shape, S- Object Size, OV – Object velocity profile, HV – Hand velocity profile, Di – Hand object distance profile.

The results show how the model is able to capture the basic object behaviour under different actions. For instance, colour is irrelevant in our setup. The shape has an effect on the object velocity (OV) and distance (Di) since tapping a ball or a box results in different effects (boxes do not roll). As expected, the hand velocity (HV) only depends on the selected action. The object hand distance (Di) also depends on the size since very big objects cannot be grasped by the robot. It is important to note that these relations are shaped by the experience of the robot and by its current skills. Another important property is that the detection of object features and effects is not perfect and the system has to cope with errors. In the same way, the same action on the same object does not always produce the same results. The probabilistic representation inherent to BN allows capturing and coping with this uncertainty.

WP5N, imitation and communication

WP5N is about imitation and communication. This Workpackage addresses 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 addressed the cognitive skills required for imitative behaviours and the cognitive skills required for communicating through body gestures. It also investigated 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 were investigated and developed with specific consideration of interaction kinesics (including gestures, synchronization and rhythms of movements etc.). Social drives for interaction, imitation and communication were considered to make use of non-verbal social cues in ontogeny in the course of human-robot interaction.

This work relies on fairly sophisticated cognitive skills which 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.

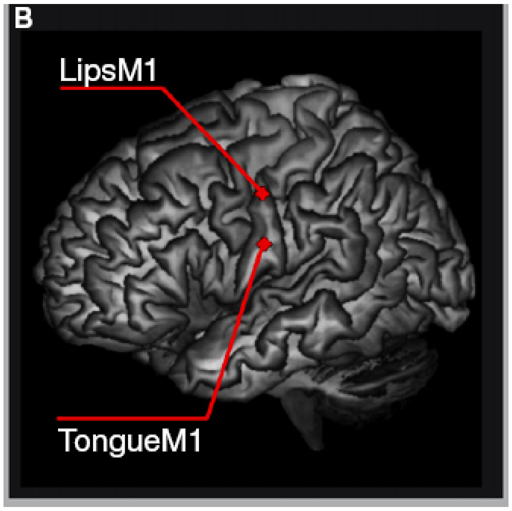
Prerequisites to these skills are the skilful control of arms and body in order to produce communicative gestures reflecting communicative timing or turn-taking, tracking and recognizing someone else's gestural timing, synchrony, and social engagement, to generalize and acquire simple communicative behaviours 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.

A large part of the iCub work in WP5N 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 work on statistical estimate of motion dynamics to allow robust estimation of arbitrary non-linear autonomous dynamical systems.

A number of human studies on various topics pertaining to the basis of human-human communication and imitation were also conducted. 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, RobotCub 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 that uses the same non-linear dynamical form as that used in the robotics imitation work mentioned above. Further experiments were directed at 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.

In particular, one quite fundamental experiment has shown that 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).

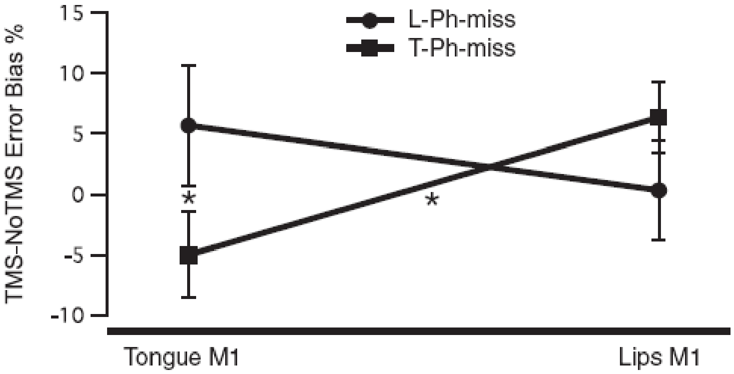


Figure 5: Accuracy results. We tested whether TMS was able to modulate the direction of errors, i.e. if the stimulation of the TongueM1 increases the number of labial sounds erroneously classified as dental and vice versa. After TMS, dissociation between stimulation site (TongueM1 and LipM1) and the 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.

WP7, mechatronics of the iCub

The objectives of Workpackage WP7 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 and the realization of several copies of the iCub by month 65. Effort was therefore allocated initially to a frenetic design activity involving mechanics, sensors, electronics, but complementary, research on motor, feedback, firmware, etc. To name a few features of the iCub, the robot was eventually set to be about 1m tall, with 53 degrees of freedom (18 of which in the two hands) and wearing a set of sensors from cameras, microphones, to force and tactile sensors. It required search for optimal components, e.g. like the frameless motors embedded directly inside the mechanical structure of the robot but also a tendon driven actuation to allocate motors in the available space. Electronics followed a similar route by being designed custom to fit the particular available space. Effort in the last periods was 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 studied specific improvements and continued the technology testing activities: for example in the field of impedance (force/torque) control.

Lately, we started versioning the iCub, since many updates were made available which improved performance considerably:
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.

In summary, the iCub has been designed to allow manipulation and mobility. For this reason 41 degrees of freedom (DOF) have been allocated to the upper part of the body. The hands, in particular, have 9 DOF each with three independent fingers and the fourth and fifth to be used for additional stability and support (only one DOF overall). They are tendon driven, with most of the motors located in the forearm. The legs have 6 DOF each and are strong enough to allow bipedal locomotion. From the sensory point of view, the iCub is equipped with digital cameras, gyroscopes and accelerometers, microphones, and force/torque sensors. A distributed sensorized skin is under development using capacitive sensors technology (iCub v2.0).

Each joint is instrumented with positional sensors, in most cases using absolute position encoders. A set of DSP-based control cards, designed to fit the iCub, takes care of the low-level control loop in real-time. The DSPs talk to each other via CAN bus. Four CAN bus lines connect the various segments of the robot. All sensory and motor-state information is transferred to an embedded Pentium based PC104 card that handles synchronization and reformatting of the various data streams. Time consuming computation is typically carried out externally on a cluster of machines. The communication with the robot occurs via a Gbit Ethernet connection.

The overall weight of the iCub is 22kg. The umbilical cord contains both an Ethernet cable and power to the robot. At this stage there is no plan for making the iCub fully autonomous in terms of power supply and computation (e.g. by including batteries and/or additional processing power on board).

The mechanics and electronics were optimized for size, starting from an evaluation and estimation of torques in the most demanding situations (e.g. crawling). Motors and gears were appropriately sized according to the requirements of a set of typical tasks. The kinematics was also defined following similar criteria. The controllers were designed to fit the available space. Table 2 **Error! Reference source not found.**shows the prototype of the iCub.

Mechanics

The kinematic specifications of the body of the iCub including the definition of the number of DOF and their actual locations as well as the actual size of the limbs and torso were based on ergonomic data and x-ray images. The possibility of achieving certain motor tasks is favored by a suitable kinematics and, in particular, this translates into the determination of the range of movement and the number of controllable joints (where clearly replicating the human body in detail is impossible with current technology). Kinematics is also influenced by the overall size of the robot which was imposed *a priori*. The size is that of a 3.5 years old child (approximately 1m tall). This size can be achieved with current technology. QRIO[7] is an example of a robot of an even smaller size although with less degrees of freedom. In particular, our task specifications, especially manipulation, require at least the same kinematics of QRIO with the addition of the hands and moving eyes. Also, we considered the workspace and dexterity of the arms and thus a three degree of freedom shoulder was included. This was elaborated into a proper list of joints, ranges, and sensory requirements at the joint level.

Considering dynamics, the most demanding requirements appear in the interaction with the environment. Impact forces, for instance, have to be considered for locomotion behaviors, but also and more importantly, developing cognitive behaviors such as manipulation might require exploring the environment erratically. As a consequence, it is likely that high impact forces need to be sustained by the robot mechanical structure. This requires strong joints, gearboxes, and more in general powerful actuators and appropriate elasticity (for absorbing impacts). In order to evaluate the range of the required forces and stiffness, various behaviors were simulated in a dynamical model of the robot. These simulations provided the initial data for the design of the robot. The simulations were run using Webots[8] and were later cross-checked by traditional static analysis.

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[7] http://www.sony.net/Fun/design/history/product/2000/sdr-4x.html

[8] http://www.cyberbotics.com/products/webots/webots5.pdf

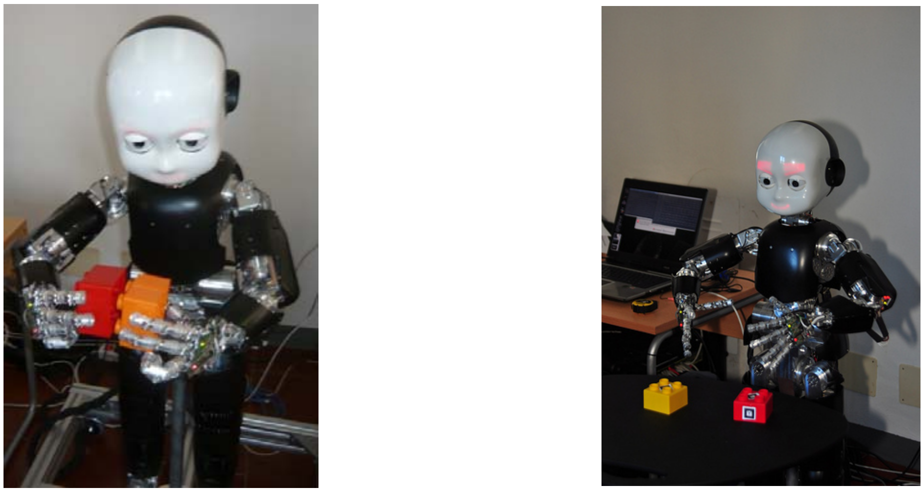

Table 2: From left to right, from top to bottom: the iCub at IJCAI, Pasadena, CA (July 2009); the iCub reaching demo being shown at the Genoa's science festival (Oct 2009); two pictures of the iCub manipulating objects at the Summer School (July 2009).

At a more general level, we evaluated the available technology, compared to the experience within the project consortium and the targeted size of the robot: it was decided that electric motors were the most suitable technology for the iCub, given also that it had to be ready according to the very tight schedule of the overall RobotCub project. Other technologies (e.g. hydraulic, pneumatic) were left for a "technology watch" activity and were not considered further for the design of the iCub. From the kinematic and dynamic analysis, the total number of degrees of freedom for the upper body was set to 38 (7 for each arm, 9 for each hand, and 6 for the head). For the legs the simulations indicated that for crawling, sitting and squatting a 5 DOF leg is adequate. However, it was decided to incorporate an additional DOF at the ankle to support standing and walking. Therefore each leg has 6 DOF: these include 3 DOF at the hip, 1 DOF at the knee and 2 DOF at the ankle (flexion/extension and abduction/adduction). The foot twist rotation was not implemented. Crawling simulation analysis also showed that for effective crawling a 2 DOF waist/torso is adequate. However, to support manipulation a 3 DOF waist was incorporated. A 3 DOF waist provides increased range and flexibility of motion for the upper body resulting in a larger workspace for manipulation (e.g. when sitting). The neck has a total of 3 DOF and provides full head movement. The eyes have further 3 DOF to support both tracking and vergence behaviors.

The actuation solution adopted for the iCub is based on a combination of a harmonic drive reduction system (CSD series, 100:1 ratio for all the major joints) and a brushless frameless motor (BLM) from the Kollmorgen frameless RBE series (Figure 6). The harmonic drive gears provide zero backlash, high reduction ratios on small space with low weight while the brushless motors exhibit the desired properties of robustness, high power density, and high torque and speed bandwidths (especially when compared with conventional DC brushed motors). The use of frameless motors permits integration of the motor and gears in an endoskeletal structure that minimizes size, weight and dimensions. Smaller motors (brushed-DC type) were used for the hands and head joints.

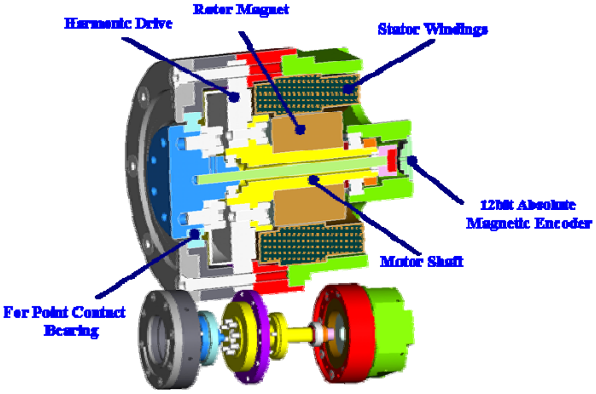

Figure 6: Section of the standard brushless motor group of the iCub. Positioning of the motor and gears can be noted (as indicated). Figure from (Tsagarakis et al., 2007). Note the compact assembly of the frameless motor and harmonic drive gear.

An example on the use of this structure is depicted in Figure 7, which shows the shoulder of the iCub with details of the motor enclosure and tendon-driven pulley mechanisms.

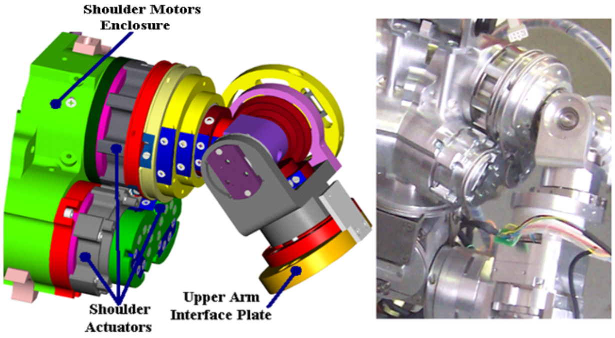

Figure 7: The shoulder of the iCub. Left: CAD schematics. Right: the implementation. Note the three DOF of the shoulder with intersecting axes of rotation and the placement of the actuators in the chest as indicated. 1.75mm steel cables join the movement of the motors with the pulleys actuating the joints.

Certain features of the iCub are unique. Tendon driven joints are the norm both for the hand and the shoulder, but also in the waist and ankle. This reduces the size of the robot but introduces elasticity that has to be considered in designing control strategies where high forces might be generated. The hand, for example, is fully tendon-driven. Seven motors are placed remotely in the forearm and all tendons are routed through the wrist mechanism (a 2 DOF differential joint). The thumb, index, and middle finger are driven by a looped tendon in the proximal joint. Motion of the fingers is driven by tendons routed via idle pulleys on the shafts of the connecting joints. The flexing of the fingers is directly controlled by the tendons while the extension is based on a spring return mechanism. This arrangement saves one cable per finger. The last two fingers are coupled together and pulled by a single motor which flexes 6 joints simultaneously. Two more motors, mounted directly inside the hand, are used for adduction/abduction movements of the thumb and all fingers except the middle one which is fixed with respect to the palm. In summary, eight DOF out of a total of nine are allocated to the first three fingers, allowing considerable dexterity. The last two fingers provide additional support to grasping. Joint angles are sensed using a custom designed Hall-effect-magnet pair. In addition room for the electronics and tactile sensors has been planned. The tactile sensors are under development (Maggiali et al., 2008).

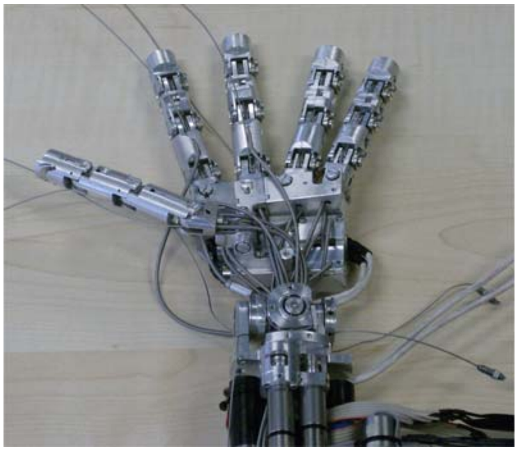

Figure 8: The hand of the iCub, showing the routing of the tendons through the wrist and some of the DOF before full assembly is completed (the palm is missing). Tendons are made of Teflon-coated cables sliding inside Teflon coated flexible steel tubes.

The overall size of the palm has been restricted to 50mm in length; it is 34mm wide at the wrist and 60mm at the fingers. The hand is only 25mm thick.

Electronics

The generation of motor control signals and sensory data acquisition is fully embedded into the iCub electronics. Further control layers are implemented externally. The interface between the iCub and the outside world occurs through a Gbit Ethernet cable. The robot contains motor amplifiers, a set of DSP controllers, a PC104-based CPU, and analog to digital conversion cards. The low-level controller cards are of two types for the brushless and the brushed-DC motors respectively. They are based on the same DSP (Freescale 56F807). The controller of the brushless motors is made of two parts (logic and power) and can deliver a current of 6A continuous (20A peak) at 48V. All supply voltages are generated internally. The CAN bus is employed to communicate with the PC104 CPU. Logic and power are 58x42mm each which can control up to two motors. The power stage mounts also a metal heatsink that is then connected to the external shell of the robot for dissipation. The controller of the brushed-DC motors is similarly made of two parts. One card acts as power supply; the other contains the CPU and amplifiers to control up to four motors. In this case the maximum continuous current is limited to 1A at 12V.

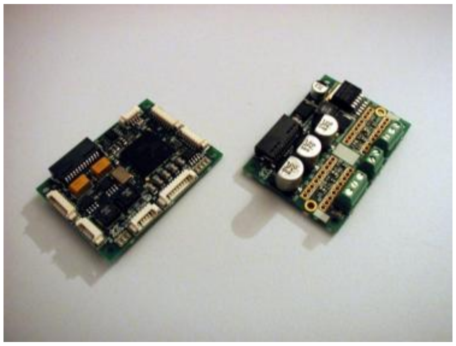

Figure 9: the brushless motor control logic and power amplifier of the iCub. Transistors were and heat sinks are not shown. The size of the two PCBs is 58x42mm.

More development is in progress to interface tactile and force/torque sensors as discussed in (Tsagarakis et al., 2007).

Sensors

Given the size of the iCub, sensors were evaluated for performance but also weight, interface standards, etc. The following table contains the list of available sensors and their status of maturity (i.e. integration into the robot hardware):

Component	Model/type	Notes
Cameras	PointGrey Dragonfly 2 640x480 30fps	Firewire cameras, support also higher resolution
Microphones	MICRO POM-2746L	Condenser electrect type
Inertial sensors	XSense MTx	3 gyroscopes, 3 linear accelerometers, compass
Force/torque sensors	Custom	Mechanically compatible with the ATI Mini-45
Position sensors	AS5045	12bit, absolute magnetic encoder
Position sensors	Faulhaber	Integrated position sensing for DC motors
Position sensors	Honeywell SS495A	Finger position sensing
Tactile sensors	Custom	Based on the AD7147, capacitive sensing

All sensors are fully integrated apart from the force/torque sensor whose control electronics is still under development and the skin whose entire technology is under testing. More information can be found in (Maggiali et al., 2008; Tsagarakis et al., 2007).

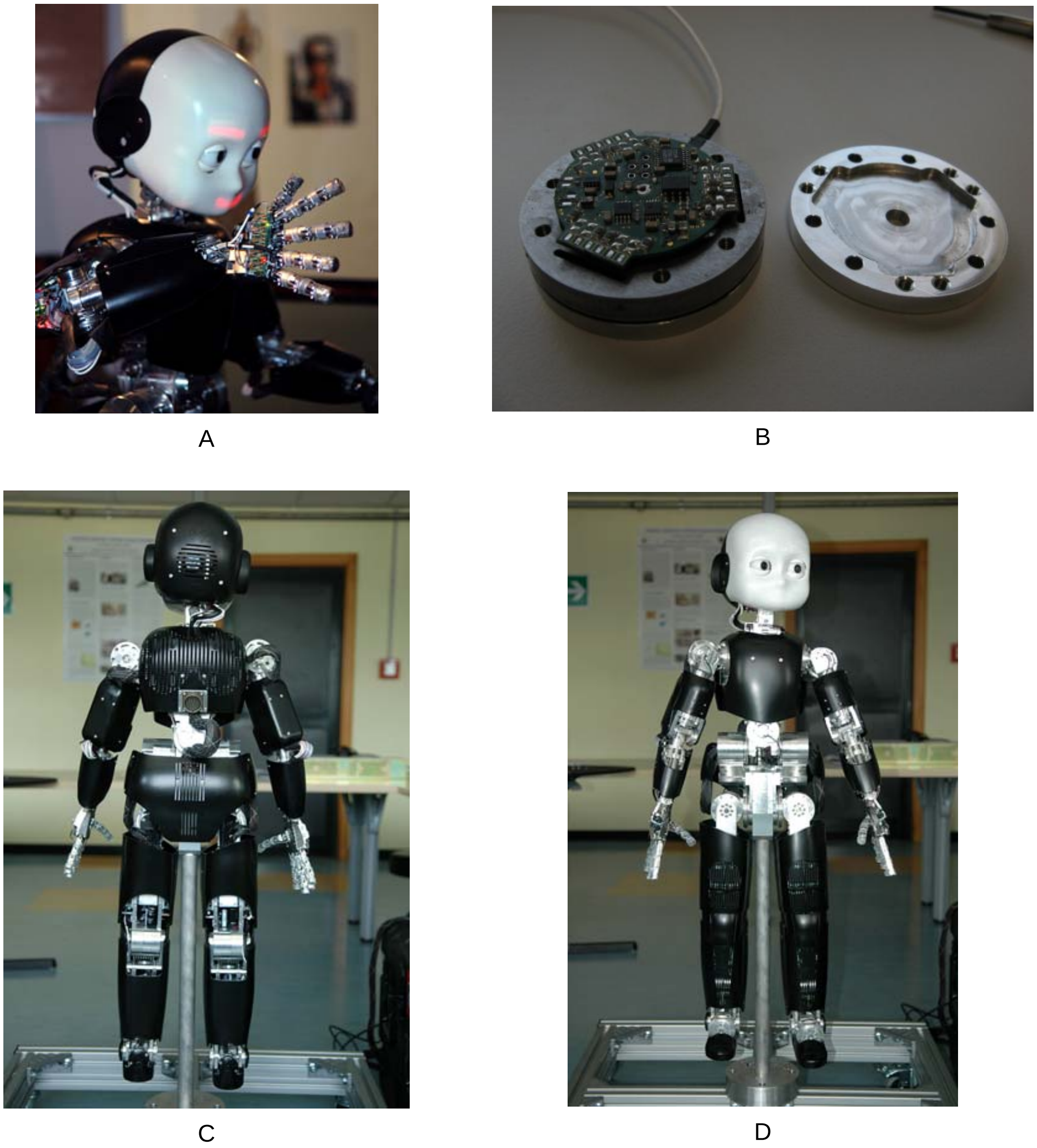

Figure 10: Some of the iCub improvements. (A) The hand with position sensor measurements; (B) The updated force-torque sensor; (C) The full body cover (back view); (D) The full body cover (front view) and new face engineering.

WP8, software architecture

The objectives of WP8 are the definition of the activity related to the creation, licensing, and distribution of the “Open Platform”, the mechanical documentation, and software standards to ensure the widest acceptability of the platform, help in defining the platform and coordinate with WP2 for requirements and WP7 for mechatronic and technological aspects, and supporting the software development on the iCub and its architecture. 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.

Workpackage WP8 had the 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. 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), to coordinate integration in order to proceed according to schedule, take 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.

Considerable effort went also into the development of a suitable software infrastructure. The iCub software was developed on top of YARP (Fitzpatrick, Metta, & Natale, 2008). RobotCub supported a major overhaul of the YARP libraries to adapt to a more demanding collaborative environment. Better engineered software and interface definitions are now available in YARP. YARP is a set of libraries that supports modularity by abstracting two common difficulties in robotics: namely, modularity in algorithms and in interfacing with the hardware. Robotics is perhaps one of the most demanding application environments for software recycling where hardware changes often, different specialized OSs are typically encountered in a context with a strong demand for efficiency. The YARP libraries assume that an appropriate real-time layer is in charge of the low-level control of the robot and instead takes care of defining a soft real-time communication layer and hardware interface that is suited for cluster computation. YARP takes care also of providing independence from the operating system and the development environment. The main tools in this respect are ACE (Huston, Johnson, & Syyid, 2003) and CMake9. The former is an OS-independent communication library that hides the quirks of interprocess communication across different OSs. CMake is a cross-platform make-like description language and tool to generate appropriate platform specific project files.

YARP abstractions are defined in terms of protocols. The main YARP protocol addresses inter-process communication issues. The abstraction is implemented by the port C++ class. Ports follow the observer pattern by decoupling producers and consumers. They can deliver messages of any size, across a network using a number of underlying protocols (including shared memory when possible). In doing so, ports decouple as much as possible (as function of a certain number of user-defined parameters) the behavior of the two sides of the communication channels. Ports can be commanded at run time to connect and disconnect.

The second abstraction of YARP is about hardware devices. The YARP approach is to define interfaces for classes of devices to wrap native code APIs (often provided by the hardware manufactures). Change in hardware will likely require only a change in the API calls (and linking against the appropriate library). This easily encapsulates hardware dependencies but leaves dependencies in the source code. The latter can be removed by providing a “factory” for creating objects at run time (on demand).

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[9] http://www.cmake.org

The combination of the port and device abstractions leads to remotable device drivers which can be accesses across a network: e.g. a grabber can send images to a multitude of listeners for parallel processing.

Overall, YARP's philosophy is to be lightweight and to be "gentle" with existing approaches and libraries. This naturally excludes hard real-time issues that have to be necessarily addressed elsewhere, likely at the OS level.

Open source robotics

RobotCub is Open Source both for software and hardware. While the phrase "Open Source software – OSS" is clear, "Open Source hardware" might sound strange, but in fact it is a plain transfer of the open source philosophy to the entire design of the RobotCub platform. The design of the robot started from the preparation of specifications (e.g. estimation of torque, speed, etc.), a typical 3D CAD modeling, and eventually in the preparation of the executive files which are used to fabricate parts and for assembly. Without good documentation it is very complicated to build and assemble a full robot. This means that documentation (as for software) is particularly important.

The CAD files, in some sense, can be seen as the source code, since they are the "preferred form of the work for making modifications to it", in the language of the GPL. They get "compiled" into 2D drawings which represent the executive drawings that can be used by any professional and reasonably well-equipped machine shop either to program CNC machines or to manually prepare the mechanical parts. This compilation process is not fully automated and requires substantial human intervention. There is a clear dependency of the 2D drawings on the original 3D CAD model. To enable the same type of virtuous development cycle as occurs in open source software, the 3D CAD is required, since changes happen in 3D first and get propagated to 2D later. In addition, assembly diagrams, part lists, and all the material produced during the design stage should be included to guarantee that the same information is available to new developers.

One difference between software and the hardware design is that there are currently no effective formats for interchange of 3D models. Proprietary systems such as SolidWorks and Pro/E can import and export a range of formats, but going from one to another is lossy, destroying information needed for production and leaving just the basic geometrical shape. So in practice, designs are tied to tools produced by a particular vendor, and interoperability between hardware design tools is limited. In RobotCub we were forced to choose a specific set of tools for mechanical and electronic CAD and future upgrades will have to strictly adhere to these standards. Due to the absence of open source professional design tools, RobotCub uses proprietary products. This is an unfortunate situation, but there is no practical alternative at the moment. The "C++" and "gcc" of CAD do not yet exist.

As a practical matter, the simple duplication of RobotCub parts does not require the use of any of these tools since we provide all executive drawings and production files (e.g. Gerber files for the PCBs). For modification, the design tools are somewhat expensive (educational discounts or educational releases exist). Free of charge viewers are currently available for all file types in question.

For RobotCub, we decided to license all the CAD sources under the GPL which seems appropriate given their nature. Associated documentation will be licensed under the FDL. These will be made available through the usual source code distribution channels (e.g. repositories, websites).

Conclusion

The design process of RobotCub has been a distributed effort as for many open source projects. Various groups developed various subcomponents and contributed in different ways to the design of the robot including mechanics, electronics, sensors, etc. In particular, a whole design cycle was carried out for the subparts (e.g. head, hand, legs) and prototypes built and debugged. The final CAD and 2D drawings were discussed and then moved to the integration stage. Clearly, communication was crucial at the initial design stage to guarantee a uniform design and a global optimization. The distributed design broke down at the integration stage where the industrial partner (Telerobot Srl. – Genoa) stepped in to carry out integration, verification and consistency checks. The design and fabrication of the control electronics was also subcontracted to a specialized company. It is important to stress the collaboration with industry for a project of this size and with these goals and requirements. For many reasons building a complete platform involves techniques and management that is better executed by applying industrial standards. One example that applies to RobotCub is the standardization of the documentation.

A further strategy used in RobotCub is that of building early. Each subsystem was built as soon as possible and copied also as soon as possible. In several cases debugging happened because the copies of the robot did not work as expected or easy to fix problems were spotted. Sometimes the documentation had to be improved. Unfortunately, this strategy was applied less extensively to some of the subparts which are or were still under design and debugging. The design stage will be completed by the realization of fifteen copies of the iCub.

This will further test the documentation and in general the reliability of the overall platform including software, debugging tools, electronics, etc. The first release of the iCub will be consolidated after this final fabrication stage.

The actual design of the robot had to incorporate manipulation by providing sophisticated hands, a flexible oculomotor system, and a reasonable bimanual workspace. On top of this, the robot has to support global body movements such as crawling, sitting, etc. These many constraints were considered in preparing the specifications of the robot and later on during the whole design process.

Both the iCub design and its software architecture are distributed as Open Source. This is not enough to guarantee success. Additional initiatives are required. RobotCub is giving away six copies of the iCub to the winners of an Open Call for proposals to use the iCub (recently concluded). In addition a structure called the Research and Training Site (RTS) has been created to support visiting researchers to work on the iCub prototypes in Genoa.

WP9, dissemination

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. Examples of the activities in WP9 include:

- 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);
- The RobotCub Consortium organized Summer School (on iCub programming) and the so-called “Winter Schools” for the Open Call winners (but also generically for all iCub owners). For instance, 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).
- The Research and Training Site (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).

Finally, we progressed by seriously (i.e. with lawyers) evaluating various possible legal entities to manage the iCub Intellectual Property after the end of the project. We plan to try the creation of a European Interest Group based on the iCub.

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, this effort has led to approximately 300 publications.

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).

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