ROBotic Open-architecture Technology for
Cognition, Understanding and Behavior

Project IST-004370

RobotCub

Development of the iCub Cognitive Humanoid Robot

Instrument: Integrated Project
Thematic Priority: IST – Cognitive Systems

Second Periodic Activity Report

Months 13-24

Period covered from **01/09/2005** to **31/8/2006**

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

Duration: **60 months**

Project coordinators: **Giulio Sandini, David Vernon, Giorgio Metta**

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

Revision: **1.0**

Table of Contents

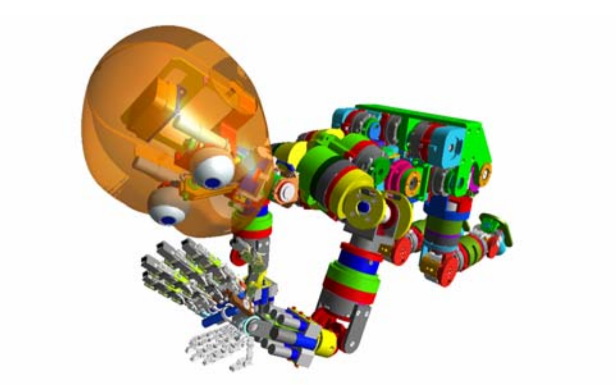
Executive Summary

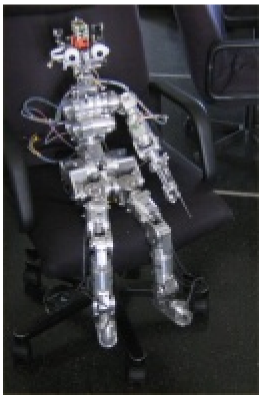
Project Summary

RobotCub is an Integrated Project funded by European Commission through its Cognition 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 will run for a total of 60 months. The consortium is composed of 10 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 project is led by Prof. Giulio Sandini, Research Director at the Italian Institute of Technology (IIT) and professor at the Dipartimento di Informatica, Sistemistica e Telematica of the University of Genoa. Project management is shared by Prof. Sandini, Prof. Giorgio Metta (with specific responsibility for the robotic platform), and Prof. David Vernon (with specific responsibility for the cognitive architecture and day-to-day management). All three are from the University of Genoa. The total funding for the project is €8.5 million.

RobotCub has two main goals: (1) to create a new advanced humanoid robot – the iCub[1] – 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.

The iCub is a 53 degree-of-freedom humanoid robot of the same size as a two year-old child. It will be able to crawl on all fours and sit up. Its hands will allow dexterous manipulation and its head and eyes are fully articulated. It has visual, vestibular, auditory, and haptic sensory capabilities.





The iCub is an open systems platform. Users and developers in all disciplines, from psychology, through cognitive neuroscience, to developmental robotics, can use it and customize it freely[2]. It is intended to become the research platform of choice, so that people can exploit it quickly and easily, share results,

[1] Cub stand for *Cognitive Universal Body*.
[2] The iCub is freely licensed under the GNU General Public Licence.

and benefit from the work of other users. This will lead to significantly greater community-wide progress in embodied cognition research.

The iCub will develop its cognitive capabilities in the same way as a child, progressively learning about its own bodily skills, how to interact with the world, and eventually how to communicate with other individuals.

Apart from the scientific aspects of the project, there is also an important component devoted to the support of the open nature of the iCub through the establishment of an international Research and Training Site (RTS). In addition to updating iCub designs, it will maintain at least three complete iCubs to allow scientists from around the world to use it for experimental research before committing to building their own iCub. The RTS will also provide a programme of training courses for scientists and students on building, using, and developing the iCub.

Furthermore, to help researchers get their own iCub, the RobotCub project will be launching a call for proposals to exploit the iCub in research projects in September 2007. Up to eight successful proposers will be provided with a complete iCub kit free-of-charge and will be provided with follow-up support to help them get started in using the iCub in their work.

Approximately €2,000,000 has been reserved for these activities in the project's budget and will be managed by the University of Genoa.

Progress and Results

Although the overall timing of the project is very tight, the project remains on schedule to meet all its major milestones.

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

Many more achievements are detailed in Section 2.

1. Over 80 papers have been published or accepted for publication. A full list is provided in Section 3 and PDF copies of these papers are available on the accompanying CD and on the RobotCub website.

2. A third prototype of the iCub head has been created, optimizing the original design developed in Lisbon (IST), and fully integrated in Genova (TLR and DIST). A fourth copy of the iCub head is being replicated using the documentation competed in Genova in Lausanne (EPFL) and three other copies of the head are currently planned for delivery to IIT.

3. The study, design and prototyping of head eyelids, facial expressions and ears is nearly completion (IST).

4. The design of the upper body and a first prototype is complete and is currently under test (TLR and UGDIST).

5. The first prototype of the lower body has been completed (UNISAL) and initial integration with the upper body and the head has also been completed (TLR, UGDIST, IST, UNISAL).

6. Three different designs of the hand were developed in parallel (UGDIST, UNISAL, SSSA). The three prototypes are completed and are under test.

7. A high power integrated actuator has been established as the standard for all the main robot axes and 23 different instances have been assembled (TLR, UNISAL, UGDIST).

8. The final version of the electronic sub-system was included in the body design to integrate as far as possible the complete system in CAD. The integration of the custom designed connectors and directly machined in the cub mechanical structure is under definition. The final specification for the complete cabling of the cub including the wire sections and pin-out is currently being specified (UGDIST and TLR).

9. A force/torque sensor suitable for mass manufacture has been designed. (UNISAL).

10. A low resolution skin sensor for the lower body has been developed (UNISAL).

11. A glove input system for motion tracking in young children has been developed. (UNISAL).

12. A high resolution finger tracking system has been developed (UNISAL).

13. The open source software architecture has been released (see http://yarp0.sf.net and http://eris.liralab.it/wiki/Deliverable_8.3) and the development of the embedded software has started (UGDIST)

14. A sophisticated control architecture based on a robot with similar kinematics and electronics has been developed; this will be ported to iCub (UGDIST).

15. An object recognition and classification model based on the work of Poggio et al. has been developed (UGDIST).

16. Several algorithms for on-line learning have been examined and customized (UGDIST).

17. The RobotCub website has been completely redesigned and a new RobotCub Wiki has been added (UGDIST).

18. The 1st RobotCub summer school was organized and run successfully; see http://www.robotcub.org/summeschool. The summer school was attended by 32 students and focussed on using the new Yarp-based software architecture (http://yarp0.sf.net and http://eris.liralab.it/wiki/Deliverable_8.3) to interact with and control two humanoid robots (James and the iCub).

19. The Roadmap for the Development of Cognitive Capabilities in Humanoid Robots (D2.1) has evolved considerably:
    - New material has been added on core knowledge, visual development, space perception, innate abilities of the neonate (UNIUP)
    - a proposed cognitive architecture has been developed (UGDIST + others)
    - a new set of experimental scenarios for the ontogenetic development of the iCub has been identified (UGDIST and UNIUP).

20. A dynamical system approach for robust reaching motions with an algorithm for learning gestures by imitation has been developed and tested on the humanoid robot HOAP3 (EPFL-A).

21. A model of the inability to interpret and reproduce meaningless gestures has been developed (EPFL-A).

22. A programmable CPG on the humanoid robot HOAP2 has been implemented (EPFL-B)

23. A study of the kinematics of baby crawling has been completed (UNIUP and EPFL-B).

24. Locomotion controllers for crawling using a CPG in the simulated iCub robot have been developed (EPFL-B).

25. A proof-of-concept has been demonstrated that a robot, in playful interactions with a person, can adapt its style of play on-line in response to the detected style of play (UNIHER).

26. Interaction experiments with KASPAR, a minimal expressive humanoid robotic platform for studying human robot interaction, have been completed; these establish acceptable parameters of robot behaviour and appearance for successful child-robot interaction (UNIHER).

27. A developmental system based on information theory has been implemented on a robot that learns a model of its own sensory and actuator apparatus (UNIHER).

28. An Interaction History Architecture has been developed to demonstrate how an interaction history, consisting of a metric space of experience, can be used by a robot to choose actions to execute based on its own categorisation if its own history (UNIHER).

29. A Peekaboo scenario has been used to study non-verbal human-robot interaction consisting of simple gestures combined to play simple interaction games (UNIHER).

30. Full-scale child-robot interaction studies involving 22 children were conducted to investigate aspects human-robot kinesics (UNIHER).

31. The KASPAR robotic platform has been developed further to include arms and wizard-of-oz GUI control software (UNIHER).

32. User studies were carried out to investigate perceptions of robotic smiles (UNIHER).

33. A design space for robots was developed based on McCloud's design space for faces (UNIHER).

34. Studies on interaction kinesics analysing effects of non-verbal robot movements and timing on human-robot interaction dynamics have been carried out (UNIHER).

35. An experimental investigation of desynchronization of an EEG rhythm in the 20 Hz band (mu rhythm) during action observation was conducted. Mu rhythm desynchronization is considered a functional correlate of the mirror system at work (UNIFE and UNIUP).

36. Preliminary Near Infrared Spectroscopy (NIRS) experiments on adults were conducted. The results of the study indicated that a multi-channel time-resolved system for functional NIRS can be successfully employed to study hemodynamic responses following motor activity in the adult brain and, more generally, to study the ontogeny of the mirror-neuron system (UNIFE and UNIUP).

37. An investigation was conducted of the gaze behavior of Autism Spectrum Disorders (ASD) children during execution of their own actions and during the observation of actions performed by others; data are still under analysis. At first sight, however, it seems that autistic children have a gaze predictive behavior comparable to that of normals (UNIFE and UNIUP).

38. A series of experiments was conducted which support to the hypothesis that that monkeys represent actions by relating relevant aspects of reality (action, goal-state and situational constraints) and that actions function to realize goal-states by the most efficient means available (UNIFE and UNIUP).

39. A multi-electrode amplifier (32 channels) has been realized and experiments were started on intracortical microstimulation in the rat ((UNIFE).

40. The collection of data acquired in monkey electrophysiological experiments is complete. These experiments aim at investigating the role of visual feedback in hand action planning and execution, and we are now analysing them. Preliminary results indicate that many motor neurons recorded in monkey's premotor area F5 are sensitive to the vision of monkey's own hand during grasping (UNIFE).

41. An experiment was conducted in which subjects were required to detect, both in monocular and binocular vision, the instant at which a demonstrator's hand firstly touched an object while grasping it. Results showed that, to accomplish the task, subjects implicitly use an internal model of the seen action, especially when the visual information is partially lacking (UNIFE).

42. The involvement of a speech premotor area (Broca's) in action understanding has been demonstrated in an fMRI experiment (UNIFE).

43. A survey of psychological models of early development has been completed (UNIUP).

44. A series of empirical studies was conducted (UNIUP):

- Unimanual and bimanual reaching (one series of experiments have been conducted on reaching for moving objects and another series on how infants look during reaching and handling objects)
- Crawling; the data is presently being analyzed at EPFL.
- Infants' imitation of adults in the object-aperture situation.
- How infants learn in a situation where they interact with several adults at once.
- Infants ability to understand and predict other peoples' actions.

45. Work has been carried out on learning sensory-motor maps, particularly for redundant systems (IST).

46. Preliminary work has been conducted on extending the ability to learn object affordances in an unsupervised manner (IST).

47. A test bed for an active vision system has been completed including the implementation of a frame grabber application in C++ based on the video for Linux 2 API specification, the C++/GTK visualization and the optical flow tracking software (UNIZH).

48. A tendon-driven robotic hand can be used both as a robotic manipulator and as a prosthetic hand UNIZH). Using this hand, the following tasks have been achieved:

- “Cheap” grasping.
- Learning to grasp.
- fMRI studies with real patients using the robotic hand as a prosthetic device.

Publications

A full list of all publications can be found in Section 3: Consortium Management. Approximately eighty papers have been published in the past year. PDF copies of publications can be found both on the project website and on the accompanying CD.

Dissemination activities

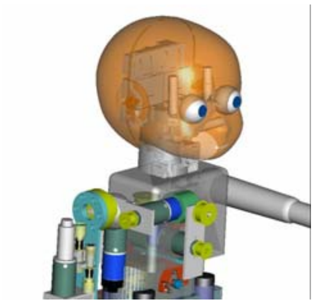
Our primary vehicle for dissemination is through publication of journal and conference papers. In addition, we have re-issued our press release and engaged in a variety of more informal dissemination activities. These are catalogued in Annex I, Section 2 below.

Use of the knowledge generated by the project

The knowledge being generated by the project is not yet at the point where it can be used, in the sense of being taken up by third parties in a transparent manner. As noted in Annex I, Section 1 below, the

RobotCub project is dedicated to the production of free-available open source results license under the GNU General Public Licence. Consequently, direct commercial exploitation is precluded. However, our explicit goal is to make the iCub humanoid robot the platform of choice for empirical research in embodied cognition and, to that end, our focus is on producing industrial grade designs and software, and making them freely available to the community on the RobotCub CVS repository.

Diagrams & photos of the work.












Section 1 – Project objectives and major achievements during the reporting period

Relation to the Current State-of-the-Art

To the best of our knowledge, the iCub cognitive humanoid robot is beyond the current state-of-the-art in developmental robotics. The empirical work on cognitive neuroscience that is being carried out by the partners is leading edge research. Together, these research efforts have led to approximately sixty publications in the past year.

Review Recommendations and Consequent Actions

The Report on Review 1 made six recommendations. The following sets out those recommendations and the actions that were taken as a result.

1. <u>Development roadmap</u> *(D2.1): By the 18 month milestone it should describe scenarios for each box, and a list of primitive abilities derived from an analysis of these scenarios. This will give a timeline for when primitives need to be on-line to meet the aims of the project.*

   The scope of WP2 is significantly extended to address the conceptual framework for cognition in RobotCub, the use of developmental and neuroscientific insights in natural cognitive systems in identifying the phylogeny and ontogeny of the iCub, and the creation of a cognition architecture by which work in other workpackages will be integrated into a complete system. Four original tasks replace by five new tasks. The title of the deliverable is amended and the revision cycle noted. Note Task 2.4 (Creation of a Cognitive Architecture) also encompasses the mapping of this framework to the software architecture being developed in Task 8.6.

   With specific reference to this recommendation, the mapping from cognitive architecture to software architecture will include the identification of specific scenarios which are broadly similar to those outlined in Table 1 – Experimental Plan in the original Technical Annex. These scenarios will be associated explicitly with specific cells or groups of cells in the Action/Development matrix presented at the review. Each scenario will identify the associated actions recruited, the type of development / learning involved, the skills developed or learned, the degree of prospection involved, the goal or purpose of the skill, the social components of interaction involved, and the perception/action primitives that are required, including both those that must be present at time zero (i.e. those associated with the phylogenetic configuration) and those that must be developed subsequently (i.e. those associated with the system ontogeny). Note that this scenario-driven approach is just one way in which the system perception/action and cognition primitives will be identified; as noted above the use of developmental and neuroscientific insights in natural cognitive systems will also be used in identifying the phylogeny and ontogeny of the iCub.

2. *<u>Robotic platform</u>: foresee intermediate releases of the robots and possibly robot components (e.g., head, hand), both hardware and software. The best way to meet the schedule necessary for getting robots to an extended consortium in time for them to have results in four years may be to get a prototype consortium working within the group of existing partners now. This may mean creating more at least partial robots for partners than are currently in the plan or budget. The number of robots to be bid on should be reduced from 10 to 8.*

   The phased release of iCub sub-systems for evaluation and revision is now explicitly incorporated into the development strategy. Even though the priority activity in WP7 is to integrate all the mechatronic components into a fully-functional and complete iCub, sub-systems, such as the iCub head, will be made available for replications when complete. This will also allow other partners to develop software utilities for these sub-systems independently of the integration work on the initial prototype.

   We have organized this phased release as follows. Each subsystem (e.g. head, arm, hand, …) is constructed by the partner responsible for the design; this subsystem is denoted version 1. The project coordinator, i.e. University of Genova, then constructs a second subsystem based on the drawings and specification released by the designers with the goal of validating the designs; this subsystem is denoted version 2. Any changes to the design required by this validation process are implemented. A third subsystem is then constructed from these final designs; this subsystem is denoted version 3. At that point, the final designs, drawings, and specifications are released as an open system. In addition to this procedure, partners that are scheduled to produce software implementations of perception/action and cognition primitives as agreed in the cognitive architecture are encouraged to build their own version 3 subsystem. To facilitate this, additional funding for the partner in question will be made available for the construction of up to two such subsystems. This funding will be reallocated from the budget for open call, reducing the number of open call systems by two as suggested in the review report.

3. *<u>Software architecture</u>: By the 18 month milestone, each lab should be in a position to set up a demo from using or producing software which uses the robotcub software architecture. This may be the only way to guarantee the software architecture is solid and the interoperability of any primitives.*

A dedicated 10-day summer-school was held on July 17-27 2006. This took the form of a hands-on practical workshop focussing on the coding and integration of utilities for perception/action control, data acquisition, and coordination on the (open-source) RobotCub software architecture. This workshop was a 'Bring your own laptop' event so that participants will leave with a complete functional system, as well as the coding and integration know-how. This summer-school was open to all member of the research community, not just members of the RobotCub consortium. There were 32 participants. This activity was undertaken as part of Task 9.3.

4. *Primitives: Tasks addressing force control and eye contact should be worked into work packages. In general, it may be a good idea to see a work package accountable for all the primitives determined as needed by the process described in the first requirement.*

   A new task (T6.2) on the detection of eye-contact was added.

   It is noted that, although the iCub will be designed so that several control strategies could be implemented, it is our intention to address specifically force control based on the use of the so-called "force fields".

   The implementation of primitives will be derived from WP2 (see Recommendation 1 above) and implemented in WP 3-6, subject to the standards and requirements of the software architecture set out in WP8. Note that a new task (T8.3) and deliverable (D8.3) have been added to address the software architecture.

5. *Website: More content on the website, e.g., by linking at least some of the existing published papers by the group to the public parts of the website. All project related documentation (and possibly software) should be made available on the project website. More effective use could be made of the website for technical project management.*

   A task for the re-design of the website has been added (T9.4). This task is now complete.

In addition I recommend to make an extra effort to increase the European and global visibility of Robot Cub within relevant communities, for instance by involving to a greater extent than has been the case in the past, the non-European (and non-funded) partners; the summer school planned for year 2 also presents an excellent opportunity in that regard.

Also on the basis of this remark on the opportunity to get a more timely and wider involvement of non-funded partners, we decided to organize the summer school on the coding and integration of utilities for perception/action control, data acquisition, and coordination on the (open-source) RobotCub software architecture (see above). Besides this action, although no explicit changes have been made to the Year 1 revision of Annex I in this regard, the consortium will redouble its efforts to achieve both strong visibility in the relevant research communities and their involvement in contributing to the creation of an open platform that will gain wide acceptance. We note in passing that, to date, papers and/or abstracts describing the RobotCub project in general have been published in Humanoids '04 & '05, ICDL '04 and '05, EpiRob '05, and AISB '05. Other papers and/or abstracts describing more specific issues in the project have either been published or submitted for publication in ICDL '05, CIRA '05, EpiRob '05, Connection Science, Artificial Life and Robotics, and the 2005 Meeting of the Society for Neuroscience.

Objectives for the Current Period

We had six principal objectives for the past year:

1. To move ahead on schedule with the design, fabrication, integration, and test of the iCub,
2. To continue with the cognitive neuroscience empirical investigations in an effort to identify the phylogenetic and ontogenetic processes underpinning cognition
3. To develop computational models of some of these processes, specifically in the areas of sensori-motor coordination, discovery of affordances, imitation, gesture and elementary agent-agent interaction;
4. To create a straw-man cognitive architecture into which these models can be integrated
5. To create a software architecture that will enable the cognitive architecture to be effectively implemented on a multi-processor control systems.
6. To attract 3rd party interest in the iCub through a combination of dissemination activities, summer schools, the re-design of the project website.

As will be evident from the 48 results listed in the Executive Summary, all of these six objectives have been achieved.

Section 2 – Workpackage progress of the period

WP1 – Management

The activity and results of this Workpackage are reported in Section 3 of this report.

WP2 – Cognitive Development

Workpackage objectives

In this workpackage, we study the development of early cognition and how to model the relevant aspects of such process within the boundaries of an artificial system. In particular, we investigate the timeframe of a developmental process that begins to guide action by internal representations of upcoming events, by the knowledge of the rules and regularities of the world, and by the ability to separate means and end (or cause and effect). 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.

Biologically plausible models of how early cognition evolves are being investigated, taking into account both the brain mechanisms underlying the modeled cognitive processes and the learning procedures used by the child to accommodate new concepts and assimilate already acquired ones to better fit the outside world. These models will be validated against behavioral studies of how young children solve problems of various kinds and how they use internal representations of objects and events to plan actions.

Progress towards objectives

UGDIST

Considerable effort has been expended in the past year in developing Deliverable D2.1 A Roadmap for the Development of Cognitive Capabilities in Humanoid Robots.

Part II has been extensively restructured and new sections added on core knowledge, visual development, space perception, and the summary of innate core abilities of the neonate. Material from all these sections was contributed by UNIUP.

New material has been added in Part V, specifically on the baseline phylogenetic configuration of the iCub, a proposed cognitive architecture, and a new set of experimental scenarios for the ontogenetic development of the iCub. This material includes a new section contrasting the different paradigms of cognition, an extensive survey of cognitive architectures with a comparative analysis, and a section on setting out the implications for development of cognition. This survey and analysis forms the basis of the proposed cognitive architecture. The roadmap also considers the possibility of interconnection between phylogenetic skills and prioritizes their implementation.

Much of the survey work on cognitive architectures has been encapsulated in a paper accepted for publication in the IEEE Transactions on Evolutionary Computation, Special Issue on Autonomous Mental Development (see Vernon_Metta_Sandini_06).

UNIFE

In an fMRI experiment UNIFE have demonstrated the involvement of a speech premotor area (Broca's) in action understanding. The paper describing the experiment has been accepted for publication in Social Neuroscience (Fadiga L., Craighero L., Fabbri Destro M., Finos L., Cotillon-Williams N., Smith A.T., Castiello U., *Language in shadow*).

UNIUP

UNIUP worked on the revision of the Cognitive Roadmap and surveyed psychological models of early development.

IST

The work of IST in this WP continued within the development framework presented last year. The development stages can be roughly organized as:

i) Learning about the self (sensory-motor coordination)
ii) Learning about objects (grasping and affordances)
iii) Learning about others (imitation)

During phase i), the robot executes "random" movements while observing the images of its own arm/hand. Since both proprioceptive and visual information are simultaneously available, it is then possible to learn a Visuo-Motor Map (VMM). These maps work in two directions. They allow the robot to predict the visual consequence of its motor activity (excluding object interaction) and they also allow the robot to compute the motor commands required to reach a certain configuration (direct and inverse models).

In the second year of the project, we considered the following types of sensory-motor maps

a) Static or incremental: depending on whether positions or position increments are considered (jacobians).
b) Full or partial: the existence of redundant degrees of freedom affords more control options. Although this might be an advantage, one must adopt a strategy for better using these additional degrees of freedom. A full map will loose the redundancy by mapping all the degrees of freedom. A partial map will only restrict the DOFs necessary for a certain task, the others remain free (reduced order sensory-motor maps) to solve other tasks like energy minimization or posture control, ... IST has studied how to define and estimate sensory-motor maps for redundant arms.

c) Geometric or radiometric: in some cases sensory-motor maps represent a geometric relationship (e.g. joint angles of the arm and the corresponding image positions). In some other cases one can directly map motor information to image appearance (e.g. of the hand).

It is important to stress that these sensory-motor maps may also relate different sensing modalities: proprioceptive, vision, speech, touch etc. During the second year of the project we worked also on sound source localization and audio-motor coordination (i.e. redirecting the gaze towards a noise stimulus), which might be needed when someone talks to the iCub.

After learning (at least coarse versions) the sensory-motor maps, the system becomes able to reach and grasp objects. At this point, it can start exploring the physical properties of the world and learn about object affordances. Here we focused on learning motion models of object to track as well as on a methodology to learn object affordances from observation.

Finally, in the imitation stage, the system learns how to perform actions executed by a demonstrator. In the first year of the project, we have focused on action level imitation (close to mimicry). This year we went a little bit further, addressing the problem of interpreting the observed action and execute the same action according to one's own plan. In other words, the system would focus mainly on the task goal rather than on the precise movements executed.

Most of this work is described in a journal paper accepted for publication at the IEEE Transactions on Systems, Man and Cybernetics. The work on the different aspects of sensory-motor coordination will be presented at the IEEE/RSJ International Conference on Intelligent Robots and Systems, IROS2006.
This work is also closely related to that of Workpackages WP3, WP4 and WP5.

UNIZH

In order to understand the mechanisms underlying self-exploration, we proposed a neural network that allows the robotic hand to explore its own movement possibilities to interact with objects of different shape, size, and material and learn how to grasp them. In our implementation the motor neurons can be randomly activated, as a result the position of the servo motors is increased or decreased, which in turn made the fingers move back and forth. Eventually the fingers encountered and got in contact with an object, depending of the force and the direction of the movement, the reading of the pressure sensor on the fingers increased or decreased. Comparing the previous pressure readings with the current ones the learning mechanism taught the hand about the success of its own exploratory efforts (i.e., the active neurons controlling the robot hand were "rewarded" if the movement of the fingers exerted a higher activation of the pressure sensors or "punished" otherwise) and finally the hand learned to grasp the object successfully (Gomez et al, 2005 and Gomez et al, 2006).

A neural controller must be able to reconfigure itself to cope with environmental and morphological changes. As not all possible changes can be anticipated by the designer, the system should be capable to explore its own movements and coherently adapt its behavior to the new situations. As exemplified by our results this self exploratory activity can be very beneficial in order to make the robot more robust and adaptive. Table 1 below summarizes the morphological changes between the two prototypes of our robotic hand. As can be seen the whole construction is very different and the weight was drastically decreased. The picture on the left is the first prototype of the robotic hand build on aluminum and equipped with standard FSR pressure sensors. The one on the right is the second prototype built on engineering plastic and equipped with pressure sensors based on conductive rubber. Furthermore, changes in the power of the servo motors and in the length of the tendons made the second prototype not only lighter but stronger.

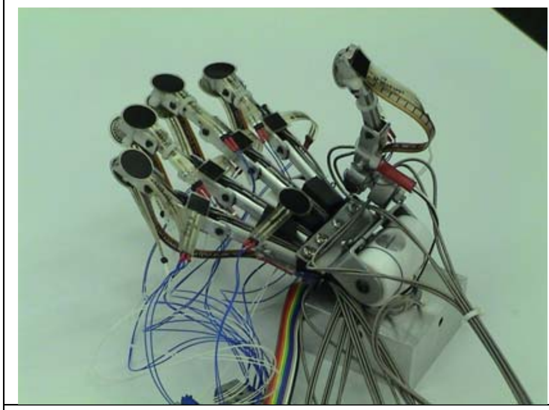
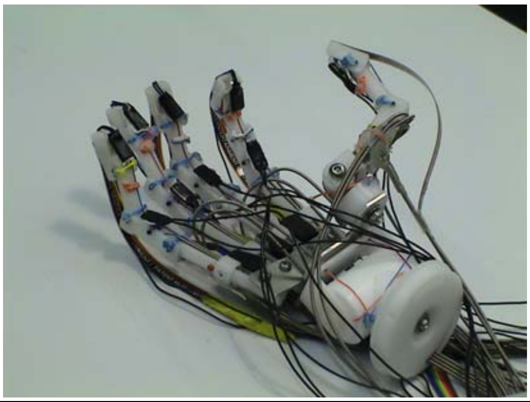
First prototype	Second prototype
	
• build on aluminum • weaker servo motors • longer tendons • standard FSR pressure sensors • 1 Kg	• built on industrial plastic • stronger servo motors • shorter tendons • pressure sensors based on conductive rubber • different actuation points • less than half of the weight of the first prototype (420 gm)

Table 1. Morphological changes

Deviations from the project work-programme

None.

List of deliverables

Del. no.	Deliverable name	Workpackage no.	Date due	Actual/Forecast delivery date	Lead contractor
D 2.1	A Roadmap for the Development of Cognitive Capabilities in Humanoid Robots	2	18, 24	18, 24	DIST

List of milestones

Milest one. no.	Milestone name	Workpackage no.	Date due	Actual/Forecast delivery date	Lead contractor

WP3 – Sensorimotor Coordination

Workpackage objectives

Activities in WP3 are aimed at the definition and implementation of the development of sensorimotor skills and their contribution to cognitive developments. UNIFE is coordinating the contribution to the activities of this WP. This WP will contribute mostly to the implementation of cognitive abilities in the artificial system. This objective will be demonstrated through extensive testing of the robot's cognitive abilities in realistic situations, implemented in several of the existing robotic platforms, as well as through psychophysical and behavioral studies measuring the robot's interactions with humans. Our goal is to investigate the following cognitive aspects underlying the development of infants' manipulation behaviors:

a) The ability of learning and exploiting object affordances in order to correctly grasp objects on the basis of their use.
b) The ability of understanding and exploiting simple gestures to interact socially.
c) The ability of learning new manipulation skills and new communicative gestures.
d) The ability of correctly interpreting and imitating the gestures of a human demonstrator.

Progress towards objectives

UNIFE

UNIFE is mainly involved in experiments investigating the development and the characteristics of the capability to plan, execute and recognize actions. Three are the main experimental approaches used for this purpose: monkey electrophysiological studies based on single neurons recordings; psychophysical studies in normals and patients (both adults and children); brain imaging and transcranial magnetic stimulation studies in normals. To better discuss experiments already planned or partially executed in collaboration with UNIUP on the development of the mirror neuron system, senior scientists of UNIFE (L. Fadiga and L. Craighero) and UNIUP (C. von Hofsten and K. Rosander) met in Uppsala from the 4th of August to the 11th of August 2006.

Ontogenetic cues in sensorimotor coordination (WP3)

Together with UNIUP we have individuated three main different techniques to study the development of action recognition in children and, during the period from Month 13 to Month 24, we have achieved the following results:

1. Mu rhythm desynchronization during action observation.
   During action execution and observation there is a desynchronization of an EEG rhythm in the 20 Hz band (mu rhythm) recorded, at rest, on central derivations. Mu rhythm desynchronization is considered a functional correlate of the mirror system at work. The meeting in Uppsala was fundamental in understanding that the first approach we used was ineffective: presentation of video

clips to 6 month old infants is not able to catch their attention. In the new version of the experiment that we tested during some preliminary sessions, a real person acts in front of the baby, playing with some toys (i.e. grasping, manipulating and placing them). We discussed together with UNIUP the parameters of the experimental paradigm as far as data acquisition and different experimental conditions are concerned. In particular, we decided that, being in a real situation, it becomes possible to acquire EEG signals also during actual grasping execution by the infant. The comparison between action observation and action execution would give a crucial improvement in the understanding of the development of the mirror neuron system.

2. Near infrared spectroscopy (NIRS).
   Brain imaging techniques (PET and fMRI) are not usable on infants because of their invasiveness and because their require subjects' immobility. In recent years NIRS has been developed to non-invasively measure regional blood flow in infants. It allows detecting the regional modifications of blood flow by spectroscopically measuring the absorbance of low-power infrared light by regional hemoglobin concentration. In order to investigate the applicability of the NIRS technique in the study of cognitive functions and to verify which method is the most suitable, we have conducted preliminary experiments on adults, in collaboration with a group of researchers from the Politecnico di Milano, leaded by Rinaldo Cubeddu. We have used a "Photon Counting – Time of flight" NIRS machine and we are, at the same time, developing a continuous-wave system as well. On this preliminary study, a paper (Craighero L., Fadiga L., Torricelli A., Contini D., Pifferi A., Spinelli L. and Cubeddu R. *Mapping cerebral hemodynamics of the human motor cortex by multi-channel time-resolved near-infrared spectroscopy*) has been presented at the 12th Human Brain Mapping Annual Meeting (Florence, Italy, June 11-15, 2006) . The results of the study indicated that a multi-channel time-resolved system for functional NIRS can be successfully employed to study hemodynamic responses following motor activity in the adult brain. In addition, the system was able to discriminate the antero-posterior extension of hand-related motor activation and the somatotopy of hand and shoulder motor representations. Moreover, the system was sensitive enough to significantly determine cortical motor activation in single trials. All these characteristics are strongly in favour of the possibility to use this technique in infants to study the ontogeny of the mirror-neuron system.

3. Gaze tracking during action observation and execution
   The pattern of eye movements during action observation is the same as that recorded during action execution. In both cases, the eyes anticipate the hand and reach the target well before the arrival of the fingers. Thus, saccadic behaviour during action observation supports the direct matching hypothesis for action recognition. We decided to study the development of this predictive behaviour during action observation in developing infants (UNIUP) and in children affected by Autism Spectrum Disorders (ASD) (both UNIUP and UNIFE). Moreover, the amount of time spent in observing stimuli presented in different experimental conditions is a dependent variable able to give information on the mental state of subjects that are not able to verbally communicate, such as infants and non-human primates. We have used this approach to study action recognition in behaving monkeys. To perform

the experiments, UNIUP and UNIFE have used the same type of eye tracking system (TOBII, Sweden).

3.a) ASD patients. It is well known that autism spectrum disorders (ASD) are characterized by deficits in social and communicative skills. It has been proposed that the mirror-neuron system may play a critical role in higher order cognitive processes such as imitation, theory of mind, language, and empathy. Strikingly, these skills are among those mostly impaired in ASD individuals. Because of this correspondence, many have suggested that individuals with ASD may have mirror neuron system impairments, and some experimental evidence supports this interpretation. Therefore, we decided to investigate the gaze behavior of ASD children during execution of their own actions and during the observation of actions performed by others. We have tracked the gaze of 8 high functioning autistic children while they were performing a modification of the Flanagan and Johansson paradigm, by using a version of the TOBII system that allows the recordings also during a real action (i.e. not presented by a video clip). We have tested also 5 normal children as a control group.
Subjects have been submitted to four different experimental conditions:

- grasp with their right hand a toy placed on the table and put it into a container *(active condition)*
- observe the experimenter performing the same action with his right hand in front of them *(passive condition, frontal)*
- observe the experimenter performing the same action with his left hand in front of them *(passive condition, frontal-reversed)*
- observe the experimenter performing the same action while seated on the same side of the children (participants saw the moving hand in an "egocentric perspective") *(passive condition, lateral)*

We had to solve a number of technical issues since the recording system needs a distance of 60 cm from the eyes of the subject. This becomes a problem when working with children that have short arms, since during action execution the arm passes through the infrared beam pointing to the eyes necessary for the recording of eye position. We solved this problem by placing the working space on a glass table, and the TOBII under it. Moreover, we recorded also the kinematics parameters by using the QUALYSIS system in order to accurately correlate the movements of the eyes and of the arms, and to verify the presence of differences between ASD patients and normal control subjects. Given the huge amount of data recorded in each trial, data are still under analysis. At first sight, however, it seems that autistic children have a gaze predictive behavior comparable to that of normals.

3.b) Behaving monkeys

Some authors have proposed that one-year-olds represent actions by relating relevant aspects of reality (action, goal-state and situational constraints) and assuming that actions function to realize goal-states by the most efficient means available. A series of experiments give support to this hypothesis. In order to verify the presence of action recognition in monkeys we applied a paradigm very similar to that used in infants.

Gaze position in one monkey was tracked during observation of different types of actions performed by the experimenter in front of it. The experiment was subdivided into two different sessions: a "familiarization" session and a "test" session. During the familiarization session the experimenter overcame an obstacle with her arm in order to reach and grasp an object. During the test session the experimenter performed two different types of movements to grasp an object in the absence of the obstacle: "congruent" condition in which the trajectory of the experimenter's arm is a normal one, and the "incongruent" condition in which the trajectory of the arm simulates the presence of the obstacle. In the infants experiment results indicated that they looked significantly longer at the incongruent test display (old jumping approach) than at the congruent one (novel straight-line goal-approach). The authors interpret this result as an evidence of an inference on the correctness of action execution. We are still analyzing the data, but it seems that monkeys behavior is very similar to the infants one, indicating that also non-human primates are able to recognize the correct way to execute an action according to the presence of situational constraints.

Phylogenetic cues in sensorimotor coordination (WP3)

UNIFE is following two different lines of research and in the following we provide a description of the major achievements obtained during the last year:

1) Single neurons recording in rats. (Task 3.5)

We are exploring the possibility that a mirror-neuron system exist not only in primates but also in simpler animals such as rats, characterized by an intense social interaction. To this purpose, we projected and realized a multi-electrode amplifier (32 channels) and we started experiments of intracortical microstimulation in the rat, in collaboration with the University of Parma (Italy) and the University of Odessa (Ukraine). A detailed description of this experiment is given in Deliverable 3.1.

2) Single neurons recording in monkeys.

We have now finished collecting data acquired in monkey electrophysiological experiments aiming at investigating the role of visual feedback in hand action planning and execution, and we are now analysing them. Summarizing, we have recorded three hemispheres from two monkeys, and the data analysis will indicate us if we need to record from another hemisphere. Preliminary results indicate that many motor neurons recorded in monkey's premotor area F5 are sensitive to the vision of monkey's own hand during grasping (WP3 and WP4, see Deliverable 3.1). Moreover, a technical paper on an automatic spike sorting using extraction of Principal Components of spike shapes has been presented in a poster format at the CogSys II (University of Nijmegen, The Netherlands, 12-13 April 2006) (Oliynyk A., Bonifazzi C., Gesierich B., Finos L., Fadiga L. *Spike sorting with linear algebraic transformation of spike shapes using LabVIEW software: an application for single unit recordings*).

Schemas in artefacts for sensorimotor coordination (WP3, Task 3.2)

UNIFE has submitted a paper for publication (Craighero L., Bonetti F., Massarenti L., Canto R., Fabbri Destro M., Fadiga L. *Temporal prediction of touch instant during grasping observation*) describing an experiment in which subjects were required to detect, both in monocular and binocular vision, the instant at which a demonstrator's hand firstly touched an object while grasping it. Grasping movements were performed with two different orientation of the fingers. Results showed that, to accomplish the task, subjects implicitly use an internal model of the seen action, especially when the visual information is partially lacking. More details will be presented in the 30 month upgrade of Deliverable 3.1

EPFL

EPFL-A have worked on extending the use of their controllers for visuo-motor coordination in the iCub for robust goal-directed reaching motions without singularities [HerschBillard06-EMBS] to tackle robust visuo-motor control of the 2 arms for simple manipulatory tasks.

This work is done in combination with the development of algorithms for imitation learning of simple manipulation tasks and is reported in [HerschBillard06-HRI, HerschBillard06-EMBS]. This is work in progress, and its contribution to WP3 will be described in more details in the next iteration of this deliverable (i.e. Deliverable 3.1b due at Month 30).

EBFL-B has developed a programmable CPG and have applied the system for biped locomotion control and modulation on a real robot [RighettiBuchliIjspeert06, RichettiIjspeert06-ICRA]. It allows control, modulation and robust integration of sensory feedback during locomotion control.

EPFL-B and UNIUP studied the kinematics of crawling babies; see [RighettiIjspeert06-RSS].

EPFL-B developed a CPG able to reproduce the main features of crawling babies, including a physically realistic simulation of the iCub in Webots. Smooth modulation of the speed of the robot was also achieved [RighettiIjspeert06-RSS].

The main achievements of EPFL include:

- integration of dynamical system approach to achieve robust reaching motions with algorithm for learning gestures by imitation and its testing on the humanoid robot HOAP3
- Programmable CPG and its testing on the humanoid robot HOAP2
- Study of the kinematics of baby crawling
- Control of crawling using a CPG in the simulated iCub robot

A movie describing work conducted by EPFL-A as part of WP3 and WP5 is available at:
http://lasa.epfl.ch/videos/control.php entitled *Dynamical Visuo-motor control*

This video relates [HerschGuenterCalinonBillard06].

A web page describing the crawling of the iCub and the collaboration with UNIUP is available here: http://birg.epfl.ch/page63115.html

See also the following page for work and movies by EPFL-B on biped locomotion control:
http://birg.epfl.ch/page56604.html

UNIHER

UNIHER completed deliverable D3.2b “Results of experiments on the autonomous development of cortex-like somatosensoritopic maps and directed behaviour”. This deliverable presents results from experiments performed with a developmental system based on information theory implemented on a real robot, that learns a model of its own sensory and actuator apparatus. Central to the presented work is the “sensory reconstruction method”, where sensoritopic maps are created that show the informational relationships between sensorimotor variables, where sensors that are informationally related are close to each other in the maps. Acting in the environment the robot, through “motor-babbling”, derives a set of rules or sensorimotor laws describing the effect of actuator settings on the sensors, which can in turn be used to perform movements guided by the sensors.

UNIUP

As part of Task 3.1, UNIUP had planned to have the iCub head at the lab in the summer to train it on the object tracking at the moving object display, but the Lisbon team advised that it would be better to do this later. The moving object display is perfect for this task because of its well defined object movements that cover very large visual angles (at least 120-140 deg.), the registration of head movements with QUALISYS, and the ability to evaluate different proportion of eye-head movements to optimize the system. We can then also compare those results with infants and adults performing the same task.

In Tasks 3.2 and 3.3, UNIUP have done several different reaching studies, both unimanual and bimanual. One series of experiments have been conducted on reaching for moving objects and another series on how infants look during reaching and handling objects.

The first set deals with infant reaching for moving objects that move on sinusoidal and circular paths. The velocity is either constant over the whole path which makes it look like the object is speeding up towards the end points of the trajectory, or it is sinusoidally modulated which makes it look like it is moving with constant velocity. The results are not yet fully analyzed but they indicate that the objects that move with constant velocity are easier to catch. In other words, while sinusoidal motion look more uniform, the one with constant velocity is easier to catch.

The purpose of the second experiment was to measure the timing of hand, head and eyes when an infant moved an object to a goal. The eye movements were measured with EOG, and all movements were performed in the frontal plane. An age group of 10 to 12 months was chosen, as infants then start moving objects in front of them and they tolerate the eye electrodes and position markers. So far 14 infants have been studied, and around 20 to 30 trials per infant are in the process of being coded. A Matlab program has been designed for the analysis of hand-head-object-eye movements. One purpose was to find out if the gaze reaches the goal before the hand, similar to the Flanagan-Johansson paradigm in adults. The experiment has not been finally analyzed but preliminary results suggest that mainly 3 types of arm-hand movements occur: 1. the infant picks up the object and moves it to a position straight in front of them. After holding and carefully looking at the object, the infant changes hand and moves it to a “goal”. In this case, the infants often track the object during the second phase of the movement. 2. The object is picked up and rather sloppy way and moved rapidly to the side in a throwing movement. The eyes usually lag in this situation or stays straight ahead. 3. The object is picked up and moved with the first hand to a goal. The gaze arrives there before the hand.

In Task 3.6, a series of studies on crawling has been performed this year and the data is presently being analyzed by Auke Ijspeert's group at EPFL.

UGDIST

UGDIST has been experimenting on existing platforms and setups on the following topics:

1. Ball catching in an experiment to investigate whether humans predict trajectories re-using internal models used normally for motor control: e.g. gravity.
2. Learning of the arm dynamics: estimation of gravity and other dynamical parameters, using parametric and non-parametric models for comparison.

We have started the development of sophisticated control architecture based on a robot with similar kinematics and electronics; this control architecture will be ported to iCub.

UNIZH

Grasping

UNIZH investigated how the shape adaptation can be taken over by morphological computation performed by the morphology of the hand, the elasticity of the tendons, and the deformability of the material covering the finger tips, as the hand interacts with the shape of an object. When the hand is closed, the fingers will, because of its anthropomorphic morphology, automatically come together. For grasping an object, a simple control scheme, a "close" is applied. Because of the morphology of the hand, the elastic tendons, and the deformable finger tips, the hand will automatically self-adapt to the object it is grasping. Thus, there is no need for the agent to "know" beforehand what the shape of the to-be-grasped object will be. The shape adaptation is taken over by morphological computation performed by the morphology of the hand, the elasticity of the tendons, and the deformability of the finger tips, as the hand interacts with the shape of the object. Because of this morphological computation, control of grasping is very simple, or in other words, very little brain power is required for grasping. (Pfeifer et al., 2006; Pfeifer et al., in press).

We also implemented a learning mechanism in order that the robotic hand can learn to grasp objects by itself as described in WP2 Cognitive development (Gomez et al, 2005 and Gomez et al, 2006). If the robotic hand actively manipulates an object, there are likely to be correlations in the sensorimotor space. This "good" sensory-motor data can be exploited for perceptual categorization, adaptation, and learning. In a previous series of studies, we have investigated how the usage of correlation, entropy, and mutual information can be employed (a) to segment an observed behavior into distinct behavioral units, (b) to analyze the informational relationship between the different components of the sensory-motor apparatus, and (c) to identify patterns (or fingerprints) in the sensorimotor interaction between the agent and its local environment. These methods were applied to real robots (Lungarella and Pfeifer, 2001; teBoekhorst et al., 2003) and simulated robotic agents (Lungarella et al., 2005; Gomez et al., 2005; Tarapore et al., 2006) and we are using them now in experiments where the robotic hand is involved in grasping tasks (Lungarella and Gomez, in preparation).

Tracking

In order to detect objects moving in the environment we have implemented 2 different systems:
The first one is based on elementary motion detectors (EMDs) based on the well-known elementary motion detector of the spatio-temporal correlation type (Marr, 1982), a description of the model implemented, can be found in (Iida, 2003), that successfully implemented a biologically inspired model of the bee’s visual “odeometer” based on EMDs. The model was used to estimate the distance traveled based on the accumulated amount of optical flow measured by EMDs. Fig. 1c and 1d show the EMDs responding to motion.

The second one is based on the optic flow extraction. We used the generalized gradient method based on Spatio-Temporal Filtering (Sobey and Srinivasan, 1991; Nagai et al., 1999). A detailed explanation can be found in Fig. 2 and for an example of the performance see Fig 1b.

Software implementation of phylogenetic abilities

Yvonne Gustain is doing her Master thesis about the “ability to track objects though occlusion", she started at the lab at the beginning of September 2006. She will be using the hardware setup already built (see Fig. 1) and the existing software (see Fig. 2). Gabriel Gomez and Martin Krafft programmed a C++ implementation of a frame grabber application using the video for linux 2 specification. (See Fig. 1b). Ryu Kato and Gabriel Gomez programmed an optical flow implementation for the tracking of moving objects. The application was developed in C++/GTK. (See Fig. 1b). The optical flow extraction is based on the generalized gradient method based on Spatio-Temporal Filtering (Sobey and Srinivasan, 1991; Nagai et al., 1999).

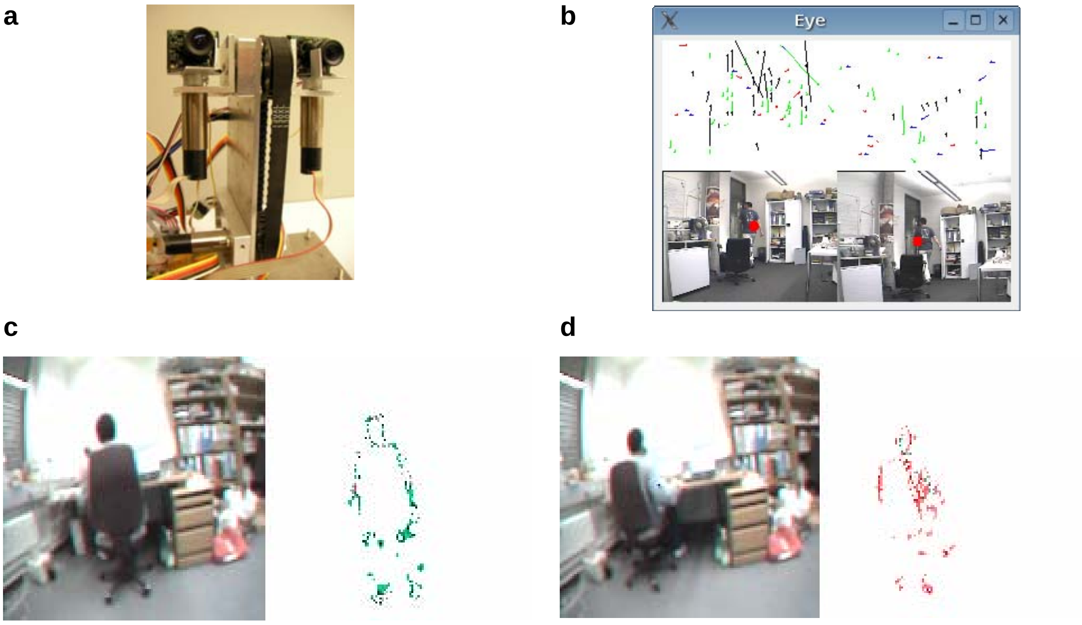


Figure 1. Active vision system. (a) Hardware implementation **(b)** the lower part consists on the left and right images captured by the cameras, the upper part are the corresponding optical flow. The red dots are the centroid of the motion (i.e., where the robot should gaze). **(c-d)** EMDs reacting to motion towards the right side of the image (green dots) and to motion to the left direction (red dots).

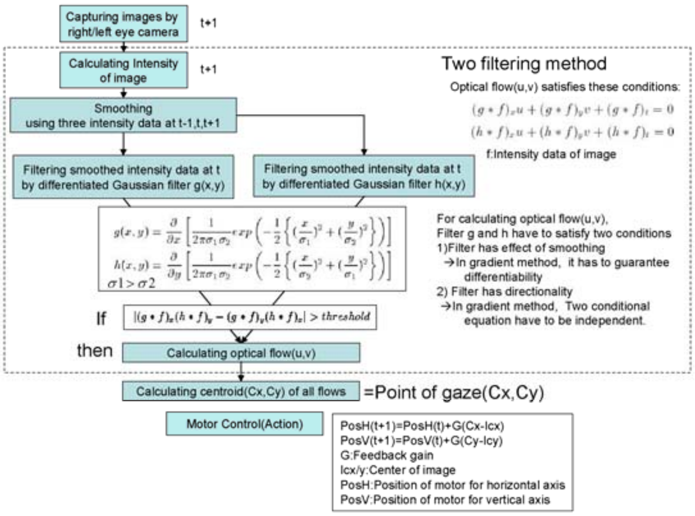


Figure 2. Optical flow extraction.

IST

As described already in WP2, IST worked on methods to build sensory-motor maps from self-observation. These maps include both static and velocity (jacobians) maps. While the static visuomotor maps are used for the first phase of grasping (reaching), the visuomotor jacobians are used for visual servoing and grasping.

Baltazar grasping an object using the learned VMM (both static and dynamic).

In the context of visuomotor jacobians (or, in other words, visuomotor dynamic maps), we continued the study of the problem of redundancy. We concluded that the use of reduced order sensory-motor maps was advantageous from the control point of view but also from the estimation (learning) point of view. The reason is that by considering reduced order jacobians the parameters to estimate become much better conditioned by the observed data. This observation is similar to the problems of “persistence of excitation” found in adaptive control.

In addition, we have studied the problem of sound source localization with two microphones (ears). While localization in the horizontal plane is achieved without too many problems (e.g. with binaural phase difference), there is ambiguity in the vertical direction. The solution adopted is inspired in the human auditory system whereby the shape of the ear Pinna leads to the absorption of different sound frequencies according to different elevation angles. This fact, in turn has been used to localize the sound source in the vertical plane and to redirect the gaze (by moving the head) towards it.

UNISAL

Within the past six months efforts at UNISAL have been directed towards:

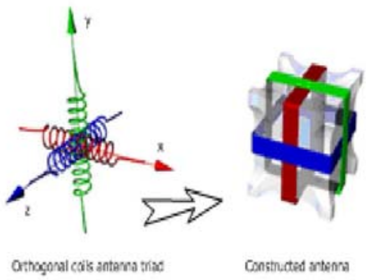
i). Development of a input tracker glove in conjunction with UNIUP looking at the development of technology to accurately track hand actions in infants up to 24 months. This work has produced a new miniaturised wireless sensory glove able to track the motions of the all finger and the thumb. The current work is developing the software interface and refining the glove design for ease of use and acceptance by the child. These refinements have been based on initial trials with children. It is expected that a new version with testing will be completed within the next recording period permitting the collection of real data.

ii). To permit a greater more accurate analysis than is currently available from glove systems a new high resolution finger tracking systems has been designed and is undergoing testing. This system has been developed based on input from UNIFE. At this time the system has been design and tested with operational software showing accurate 6 dof tracking (accuracy better than 0.1mm at finger tip). With further development this will be integrated with the work at UNIFE and UNIUP.

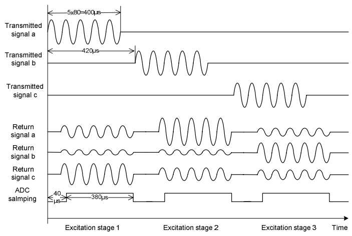
iii). Continued work on the development of an understanding of the sensory systems for legs, hips, feet and the sensory requirements of the iCUB.

Miniaturised glove systems used in Child motion Testing

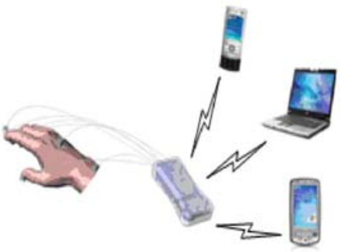
High Precision Finger Trackers



Orthogonal coils antenna for transmitter/receiver.



Transmission signals used in the detection of the joint motions



Hand tracker Bluetooth connection possibilities.

Deviations from the project work-programme

EPFL-B has also started the development of a structure of non-linear systems able to switch between rhythmic and discrete movements or to combine both type of movements. This is important for doing visually-guided hand and feet placement during crawling, and also for exploring questions on how to relate locomotion control to the control of reaching (more on this below). As a first application, we used the system for a drumming task on a real robot; see [DegallierSantosRighettiIjspeert06]. This work on the superposition of rhythmic and discrete movements will become a new task in the M25-M42 Detailed Implementation Plan.

At UNIZH, Martin Krafft left the project. UNIZH are evaluating numerous candidates to fill his position and continue his initial implementation of an adaptive learning framework in C++. We strongly believe that we cannot build the software (mind) without the hardware (body); therefore we decided to save the money for when the iCub's complete design and hardware components will be available. Now that we have an active vision system comparable to the one of iCub, we hired Jonas Ruesch on the Project. He started on the 1st of October as a Ph.D. student and he will be porting our existing software to the YARP library and making experiments in the “ability to track objects though occlusion" as well as in eye-arm-hand coordinated experiments.

List of deliverables

Del. no.	Deliverable name	Workpackage no.	Date due	Actual/Forecast delivery date	Lead contractor
D3.1	Initial implementation of models of sensorimotor coordination primitives (report and demo)	3	M24, M30	M24	UNIFE
D3.2	Initial results of experiments on the functional organization of the somatotopic maps and on the cortical representation of movements (report)	3	M18, M30	M18	UNIHER

List of milestones

Milestone no.	Milestone name	Workpackage no.	Date due	Actual/Forecast delivery date	Lead contractor

W P 4 – O b j e c t A f f o r d a n c e s

Workpackage objectives

The goal of this WP is that of exploring and modeling the mechanisms underlying the acquisition of object's affordances. This investigation can be seen developmentally as an extension of WP3. Specific models of how the primate's brain represents affordances will be considered (for example the parietal-frontal circuit) as well as results from psychological sciences. Note how much this is linked to aspects of sensorimotor coordination on one side (WP3) and of imitation and the understanding of goals on the other (WP5 and WP6). Specifically, we will investigate:

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

Progress towards objectives

UNIUP

In Task 4.1 we have worked together with Lisbon on applying our object-aperture studies to the iCub. The challenge is to get the iCub to develop skills at those problems in a way similar to how children develop them.

In Task 4.2 we are currently running experiments on infants' imitation of adults in the object-aperture situation.

UGDIST

UGDIST has been studying and implementing the so called “HMAX” or “standard model” of object recognition, due to Tomaso Poggio and his colleagues (Serre, Kouh et al. 2005). The model describes the feed forward path of the ventral stream, therefore the first 150 ms or so of visual recognition. Feedback loops and top-down influences are not taken into account in the current version of the model.
The first stage of the model consists in the extraction of local orientations with non linear filters that resemble the response of the receptive fields of V1 (simple cells). Partial invariance to scale and translations is achieved with a hard MAX operation (complex cells), then a set of intermediate level shared features is used in input to a SVM classifier to make the model useful for classification.

The performance of the model for classification on standard databases of images is similar to state of the art algorithms, while retaining the biological plausibility of each modules (Serre, Wolf et al. 2005).

Even if the model is simple, it has a lot of degrees of freedom that could be used to enhance its performances. For example in a recent work of Mutch and Lowe (Mutch and Lowe 2006) some improvements are presented, using a “sparsification” process, selecting the range of some parameters and reducing the number of features with a supervised feature selection method.

In our opinion key features of the model that could enhance the performances and the biological plausibility are the mechanism to obtain invariance to various transformations and the possibility to learn as much as possible from the statistics of the world (Orabona, Metta et al. 2006), instead of hard-wiring specific filters/methods.

Regarding the first point we are investigating different normalization procedures that seem to improve the classification rate through an improved invariance, without affecting the speed of the model.

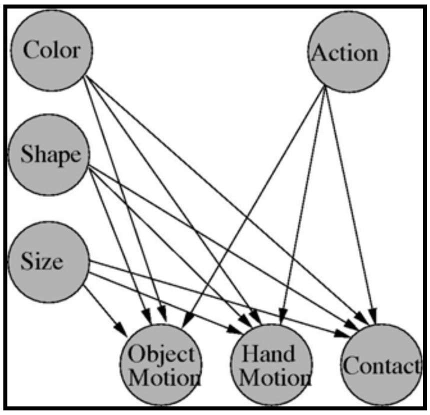
For the latter point, the learning part of the model is basic: only the intermediate level features are learned, using a random selection of parts of the training images. However it has been demonstrated that algorithm like Independent Component Analysis (ICA) and in general Sparse Coding applied to visual stimuli successfully reproduce some properties of the receptive fields of the visual neurons. In this sense it could be used to learn the optimal filters for the first stage of the model (Wersing and Körner 2003). Moreover we are investigating the possibility to prune the learned features in an unsupervised way, that is before knowing the labels of the classification task, exploiting the redundancy of the learned features. In this way it would be possible to use an on-line classification algorithm (Cauwenberghs and Poggio 2000), while it would be impossible if the knowledge of all the labels was needed for the selection.

IST

IST’s previous work on object affordances was centered on the use of those affordances for gesture (manipulation) recognition. The role played by the affordances here consisted basically on a (strong) prior elicited by the detection of the object subject to manipulation. A supervised learning of these priors was done in a very simple manner by estimating relative frequencies in training data.

We have now started to go one step further. The idea now is to develop a methodology whereby the system should be able to learn object affordances directly by observing actions upon objects. The affordance concept links pairs of actions and object characteristics to their effects (which were not considered in our previous work). In our case, this relation will be modeled in a probabilistic framework as the marginal probabilities of a Bayesian network. The use of Bayesian networks provides a generic and sound model that allows addressing learning and inference within the same framework. In addition to this, it is possible to model different learning contexts such as self-exploration, imitation or reinforcement learning. The next figure shows a simplified network of one of the experiments to illustrate the approach.

Two cases were distinguished. In one case, we assume that the network structure (nodes and their dependencies) is defined a priori and the system will learn the model probabilities, for instance, the marginal probability of an effect for an action given the object characteristics. In the second case, which is considerably more challenging), we will assume that part of the model structure is unknown a priori. Here the system must perform structural learning to obtain not only the model probabilities but also the structure of the model itself. In other words, it also has to establish what the important characteristics of an object are to attain the desired effect. So as to reduce the complexity of the learning task, we will take advantage of the biological studies to drive the exploration of the



Deviations from the project work-programme

None.

List of deliverables

Del. no.	Deliverable name	Workpackage no.	Date due	Actual/Forecast delivery date	Lead contractor
4.1	Results of experiments on affordant behaviors.	4	18, 30	18	IST

List of milestones

Milestone. no.	Milestone name	Workpackage no.	Date due	Actual/Forecast delivery date	Lead contractor
-	-	-	-	-	-

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WP5 - Imitation

Workpackage objectives

In this Workpackage, we investigate imitation of goal-directed manipulation task and imitation of simple gestures, such as pointing, waving and simple pantomiming. In particular, we will look at the following cognitive stages underlying children's imitative behavior:

a) Imitation of goal-directed arm motions (pointing and reaching for objects).
b) Imitation of the functional goal of arm motion (grasping, pushing, dropping objects)
c) Understanding the communication effect of imitation or the passage from being an imitator to become a demonstrator.

We develop functionally biologically plausible models of the brain mechanisms underlying the cognitive processes behind imitation.

Progress towards objectives

EPFL

EPFL-A worked on extending the use of our controllers for visuo-motor coordination in the iCub for robust goal-directed reaching motions without singularities [HerschBillard06-EMBS] to tackle robust visuo-motor control of the 2 arms for simple manipulatory tasks.

This work is done in combination with the development of algorithms for imitation learning of simple manipulation tasks and is reported in [HerschBillard06-HRI, HerschBillard06-EMBS].

Exploring further the dynamical system approach to robot control, this research addresses the challenge of automatically adapting a dynamical system to make it suitable for the control of a particular manipulation task. Several kinaesthetic demonstrations of the task are used to train a probabilistic model of that task. This model is then used to modulate a dynamical system which will produce the movements adequate for a successful task execution. This approach provides the robot with the learning abilities offered by the tools of statistical learning theory, and the robustness and adaptiveness peculiar to dynamical system control. The robot is thus able to perform the demonstrated task, while adapting to different initial conditions and possible perturbations occuring during task execution. Various task models, involving different variables were studied and compared [HerschGuenterCalinonBillard06-TRANS], and the system was tested for tasks such as grasping on object, putting in into a box, closing the box [HerschGuenterCalinonBillard06-RAS].

UNIHER

UNIHER has undertaken a full-scale study of child-robot interaction to study the timing of non-verbal interactions in child-robot interactions. The humanoid robot KASPAR, controlled by the investigator, played interaction games with 22 children in experiments designed to address two research questions: in what way and to what extent do expressive gestures (head nods and blinks), made by the robot contingent with its part in the interaction, affect the timing of interaction, and, does the introduction of a delay in the robot's response enhance and or regulate the timing of the interaction.

KASPAR played two different games with the children. The first was a drumming call and response game where a child played a short phrase on a tambourine and KASPAR played a similar phrase in response. This was done with and without delay and with and without accompanying head and eye movements. The second was a gesture-imitation game where the children would assume an expressive posture from the robot's repertoire which KASPAR then imitated either with or without a short delay.

Results of these studies are presented in WP5 as D5.4 "First results of experiments on mirroring and communicative aspects of imitation".

Initial analysis of the extensive data gathered suggests that timing of robot responses and use of non-verbal expressions affect humans' interaction dynamics in terms of duration and pauses during interaction, and that, moreover, there are significant qualitative individual differences between people in the particular impacts on their interaction kinesics of manipulating these variables in robot behaviour.

UNIFE

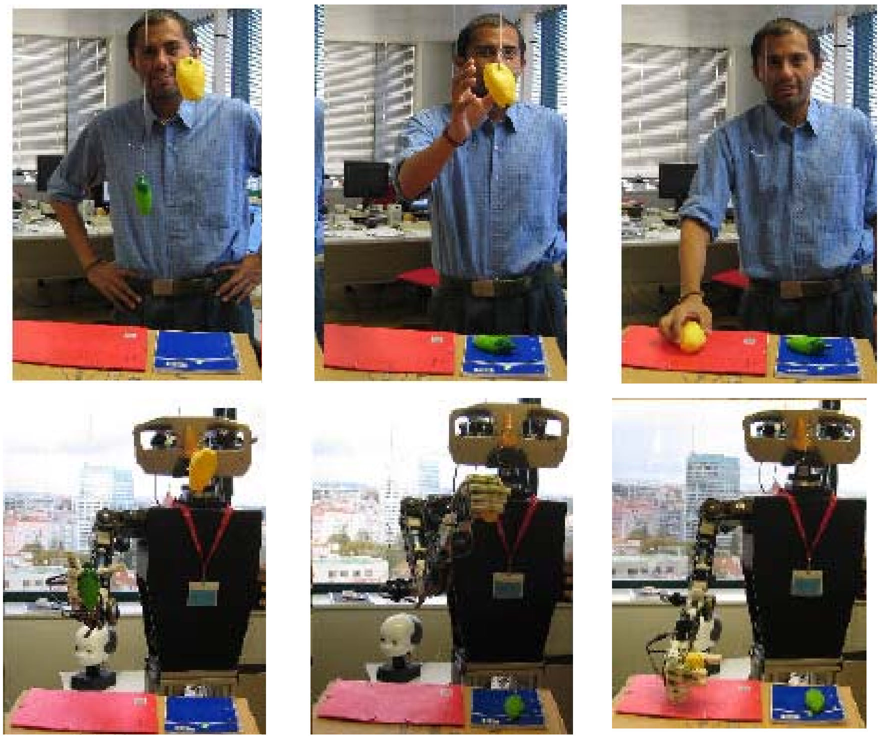
In collaboration with EPFL, UNIFE has conducted an exercise to replicate some experiments done by EPFL on the kinematics during imitation of movements. The aim of the experiment was to verify if the position of articulations influences the way in which the same action is imitated. The work has been presented in a poster format at the CogSys II (University of Nijmegen, The Netherlands, 12-13 April 2006) (Gesierich B., Canto R, Fabbri Destro M., Fadiga L., Finos L., Hersch M., Oliynyk A., Craighero L., *Study of kinematics and eye movements during imitation*).

UGDIST

UGDIST has prepared the protocol for experimenting on "mirror" effects as an extension of the ball catching experiment.

IST

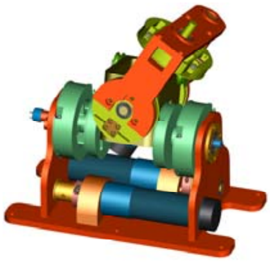
As of last year IST had developed methods whereby Baltazar could perform action-level imitation. In the second year we have looked at methods to allow Baltazar to understand the observed actions and generate a description (or plan) that could be executed later on. While executing the task, the robot will use its own motor programs whose execution might differ from the ones used by the demonstrator. The objective is to achieve the same action goals (grasping, releasing).



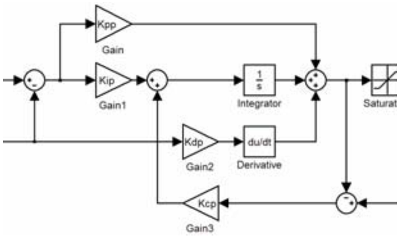
Top: Action executed by a demonstrator (object manipulation). **Bottom:** Action imitated by Baltazar after generating a description of the observed task.

UNISAL

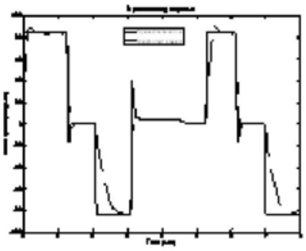
UNISAL developed low level (Joint and joint co-ordination) sensorimotor control algorithms and drivers for the iCUB, concentrating particularly on the needs and requirement of these activities for the brushless motors that are integral to the actions of the major joints.



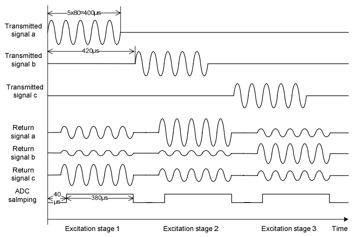
Waist design



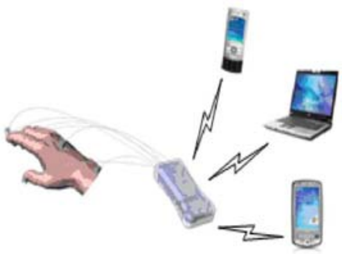
Waist Control



Results



Transmission signals used in the detection of the joint motions



Hand tracker Bluetooth connection possibilities.

Deviations from the project work-programme

None.

List of deliverables

Del. no.	Deliverable name	Workpackage no.	Date due	Actual/Forecast delivery date	Lead contractor
D 5.1	Evaluation of an algorithm for interpreting the kinematics of arm motion and its relationship to object motion.	5	6	6	EPFL
D 5.2	Implementation of visual recognition and imitation of goal-directed reaching motion.	5	12	12	EPFL
D 5.3	Implementation of goal-directed and functional imitation of simple manipulation of objects.	5	18	18	EPFL
D 5.4	First results of experiments on mirroring and communicative aspects of imitation.	5	24, 36	24	UNIHER

List of milestones

Milestone. no.	Milestone name	Workpackage no.	Date due	Actual/Forecast delivery date	Lead contractor
-	-	-	-	-	-

WP6 – Gesture Communication

Workpackage objectives

This WP focuses on the regulation of interaction dynamics of social interaction during human-robot play. The pre-requisites for interactive and communicative behaviour grounded in sensorimotor experience and interaction histories will be investigated and developed with specific consideration of interaction kinesics (including gestures, synchronization and rhythms of movements etc.). This work includes, inter alia, information theoretic methods applied to characterizing and identifying experience, mapping sensor space and learning motor capabilities.

The objectives of this WP are three-fold:

1. Development of the pre-requisites for (non-verbal) interactive and communicative behaviour grounded in sensorimotor experience and interaction histories
2. Development of a robotic test-bed for the investigation of interaction kinesics
3. Small scale user-study to investigate the space of interaction kinesics in “Wizard-of-Oz” studies

In addition to the above the description of work includes:

- investigation of the communicative aspects of gesture recognition.
- investigation into different (developmental) levels of play in human-robot interaction games
- development or acquisition of eye-contact detection software for the iCub

Progress towards objectives

UNIHER

UNIHER has continued to investigate the construction through ontogeny of interaction histories grounded in the sensorimotor experience of robots, and the use of these histories in determining future action based on past experience. Formal information-based metrics are used to construct a metric space of experience which places experiences such that similar experiences are close together and dissimilar experiences further apart. The metric space of experience combined with an action selection mechanism, a motivational subsystem and an internal feedback mechanism, together constitute a proposed interaction history architecture for robot control based on experience.

Social interaction using gesture primitives are investigated in a robot through playing of the simple interaction game “peekaboo” with a human partner. Investigations were carried out to determine the effect of the horizon length of experience on the development of the ability to play the game. Results showed that best results were achieved when experience horizon lengths were of the same order of magnitude as the period of the cyclic behaviour being executed, suggesting multiple experience spaces of varying horizon length are necessary to accommodate different interaction timings and kinesics.

UNIHER also reports on a proof-of-concept of a robot that, in playful interactions with a person, can adapt its style of play on-line in response to the detected style of play. For successful social interaction, an autonomous agent must be able to detect characteristics of the ensuing interaction and adapt and respond appropriately. A self-organising map is trained to recognise two different styles of play, “gentle” and “strong” and the robot responds appropriately.

UNIHER has continued interaction experiments with KASPAR[3], a minimal expressive humanoid robotic platform for studying human robot interaction. In addition to the expressive head, KASPAR’s 3 DOF arms greatly enhance the range of gestures and emotions that can be conveyed. Software development proceeded providing necessary capabilities to conduct wizard-of-oz type studies. Within WP6 KASPAR was used to investigate the perception of a robot smile and found that for the smile to be appealing, the timing of the transition from neutral to smiling needed to be natural (i.e. around 1 or 2 seconds).

Research showed that the design of robot appearance and behaviour matter in interaction experiments. UNIHER discuss the design space of robots for interaction experiments and report on lessons learnt.

EPFL

EPFL contributed to WP6 through the development of a neurocomputational model of the brain pathways underlying our understanding and interpretation of gestures, such as those observed in Apraxic patients. This work is described in [PetreskaBillard06]. While the model addressed so far the interpretation of meaningless gestures, this work is a first step toward the development of a concurrent model of the pathway underlying the recognition of meaningful gestures. This work is tightly linked to that conducted in WP5, for which EPFL is the workpackage leader. This part of EPFL work makes a bridge between WP5 and WP6 in addressing imitation of gestures, and, by so doing makes a first step toward understanding the role that imitation plays in interpreting and understanding communicative or not gestures.

UNIFE

A paper on an eye-contact fMRI experiment we performed in collaboration with Aldo Rustichini (Minneapolis) is in preparation. More details will be presented in the 30 month upgrade of Deliverable 3.1

UNIUP

In Task 6.2 we are investigating how infants learn in a situation where they interact with several adults at once. No results are available yet.

In Task 6.3 we are running a series of studies of infants ability to understand and predict other peoples' actions.

[3] KASPAR (**K**inesics **A**nd **S**ynchronisation in **P**ersonal **A**ssistant **R**obotics) is a child-sized humanoid robot developed by the Adaptive Systems Research Group at the University of Hertfordshire.

Deviations from the project work-programme

Child-Robot Wizard-of-Oz studies into the kinesics of social interaction games are now reported in deliverable 5.4

UGDIST diverted effort from on gesture communication to other WPs (WP7 and WP8)

List of deliverables

Del. no.	Deliverable name	Workpackage no.	Date due	Actual/Forecast delivery date	Lead contractor
D 6.1	Implementation of goal-directed and functional imitation of simple manipulation of objects.	6	12, 24	24	UNIHER

List of milestones

Milestone. no.	Milestone name	Workpackage no.	Date due	Actual/Forecast delivery date	Lead contractor
-	-	-	-	-	-

WP7 – Mechatronics of the iCub

Workpackage objectives

To define the functional specifications for the initial design of the mechatronic components of the iCub, that are the Head-Eye system, the Arm-hand systems, the Spine and Leg system and the Software Architecture. To identify the roadmap for the overall system integration, in order to guarantee the compatibility of all the iCub subsystems, both from a hardware and a software point of view.

Progress towards objectives

Despite some delays, all the current objectives have been achieved. The delays arose for a number of reasons including increase in design complexity, delays in delivery of components, and unforeseen problems with mechanical compatibility of machined parts. The planned integration of the electrical wiring in the design is still to be completed and will be based on the 1st prototype rather than starting directly on the CAD. The cover of the body is becoming locally functional (e.g. in the forearm the cover is structural and load-bearing, elsewhere in the body the cover integrates the heat-sink).

The status of realization is as follows:

- A third prototype of the iCub head, optimizing the original design developed in Lisbon (IST) was completed and fully integrated in Genova (TLR and DIST). A fourth copy of the iCub head is being replicated using the documentation competed in Genova in Lausanne (EPFL) and four other copies if the head are currently planned.
- The high power integrated actuator for the main robot axis was used as standard group for the whole body and assembled in 23 different instances. The original design was also upgraded adding and absolute position sensor on output shaft and replicated both in Genova (TLR) and Salford (USAL). A set of extensive tests on the first prototypes were carried out initially to test the actuator by itself and then as a test bed for the custom electronic boards expressly designed for this new actuator.
- Final review of the electronics was integrated in the body design to integrate as far as possible the complete system in CAD. The integration of the connectors custom designed and directly machined in the cub mechanical structure is under definition. Its feasibility was already checked. The final specification for the complete cabling of the cub including the wire sections and pin-out is currently under investigation;
- Upgrade of the tension sensor to be integrated in the finger was also done. First industrial production of a first set of tension sensor based of the first prototype and consequent modification is starting in this period;
- A 6 DoF load cell was designed and developed in Salford (USAL).The results obtained after the first couple of prototypes and consequent optimization are interesting. This sensor will be candidate to be integrated in each limb of the iCub. Replication of the sensor is already planned for the next month in Genova (DIST).

- The tactile sensor based on analog hall effect sensor was optimized and is currently being integrated in the finger design (room required to accommodate two sensors in each finger tip plus a third sensor in each intermediate phalange was already planned in the finger design).
- The upper body is totally designed and a first prototype is currently under test (TLR and DIST). Initially only the left side of the upper body was manufactured and assembled, the right side realization started in Sept 06.
- The lower body and waist were reviewed, optimizing overall shape. Mechanical drawings of the waist and lower body were completed. The first prototype of the lower body was completed by the end of Y2. The lower body is currently under test.
- Three different design of the hand were developed in parallel in Genova, Pisa, and Salford. The three prototypes are completed and under test.
- The Deliverable D7.1 was moved to the wiki web site of the project to be continuously upgraded based on the results obtained by all the group working in parallel on the platform.
- The first integration of the upper and lower body is planned for the end of Sept 06.

TLR

The main activities of TLR in the reporting period are as follows:

- Review of the mechanical documentation of the last prototype of the IST head with overall review of the 2D documentation. Partial upgrade of the original design with the introduction of higher torque, higher efficiency gearboxes on the two first axis of the neck. Electronic integration on the head. Review of the face model with new materials evaluation. Design optimization and review based on the first set of tests done at DIST.
- Integration of the electronics (amplifiers, capacitors and DSP) in the mechanical design of the upper body, preliminary heat sink design and first integration of heat dissipation in the robot cover.
- Integration of absolute position sensor on output shaft of high power servomotor;
- Detailed mechanical design with full mechanical documentation (2D drawing) of the upper body (left and right part) including the upper torso, the shoulder, the upper arm including the elbow, forearm and hand (right forearm and hand currently under completition).
- Review of the general lower body layout and overall shape optimization.
- Redesign and optimization of the tensile load cell to be integrated in all the hand fingers.
- Optimization on the finger design based on a full scale finger and actuator group with spring underactuation optimization.
- Integration of the first high torque motor in a test bed for motor and control evaluation.
- Integration of the LIRA copy of the iCub head and subsequent optimization and mechanical tunings;
- Completed the design of the iCub upper body including shoulders, elbows, wrists, hands;
- Replicated a copy of the IST designed head. Amended and optimized the design following the results of the first test done at DIST and optimized the prototype.

- Built a prototype of the upper body (initially only the left shoulder and elbow – left forearm and hand as well as right arm are soon coming);
- Coordination on the consortium design activity.

UGDIST

During this period, UGDIST has been:

1. Coordinating the realization of the iCub.
    a. Mechanics together with TLR, SSSA, UNISAL, IST.
    b. Electronics though subcontractors.
2. Continuously checking conformance to specifications of the robot design.
3. Realizing a copy of the iCub upper body (partial).
4. Verifying integration.

IST

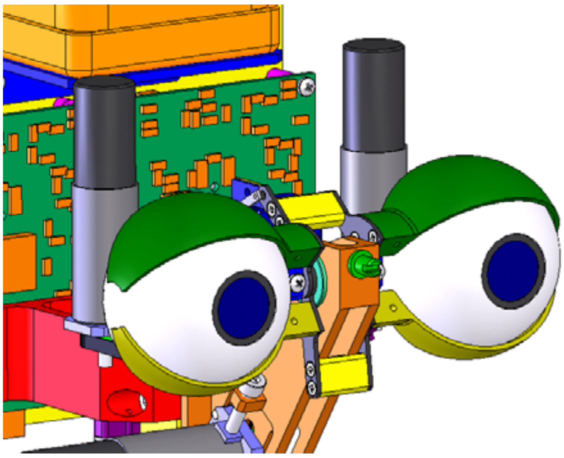
During the first year, IST designed the iCub head, after exploring several possible designs. The designed head is very modular and compact and was demonstrated at the first year review meeting and was one of the setups used in the summer school (motion capabilities, light tracking with 6 DOFs and head pose stabilization with vestibular information). Also the face cover design was demonstrated during the first year review.

In the second year we redesigned some head parts with the following goal:

- Allow for additional weight being added to the head. Due to lack of space in the body, some additional electronics had to be placed in the head, increasing the required torques.
- Optimization of overall mechanism for additional robustness and ease of maintenance.

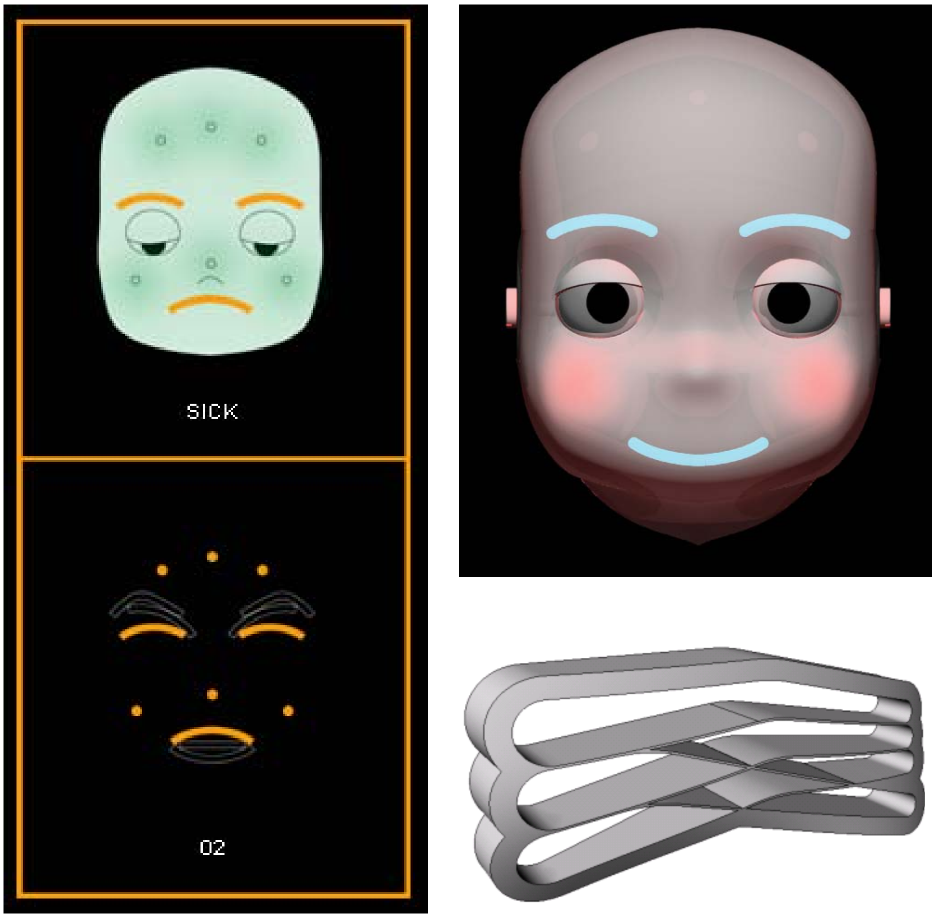
A recurrent discussion in the project is related to the ability of the robot to express its “emotional” status when engaged in social interaction. This concern was not initially included in the Robotcub proposal but was addressed in the following lines:

- After studying several concepts for the face design, we adopted a cartoon-like face appearance that seems to elicit empathy with the system.
- Several discussions indicated that the ability to include moving eyelids would be very important to express fatigue, annoyance or surprise. We have designed a compact mechanism for adding eyelids to the head.
- The ability to further convey the “emotional” state of the robot also led to the idea of eyebrows and mouth expressions. Due to extreme space and weight constraints in the head, we have chosen to build this capability using sets of LEDs for the mouth and eyebrows that can be illuminated in various different ways.



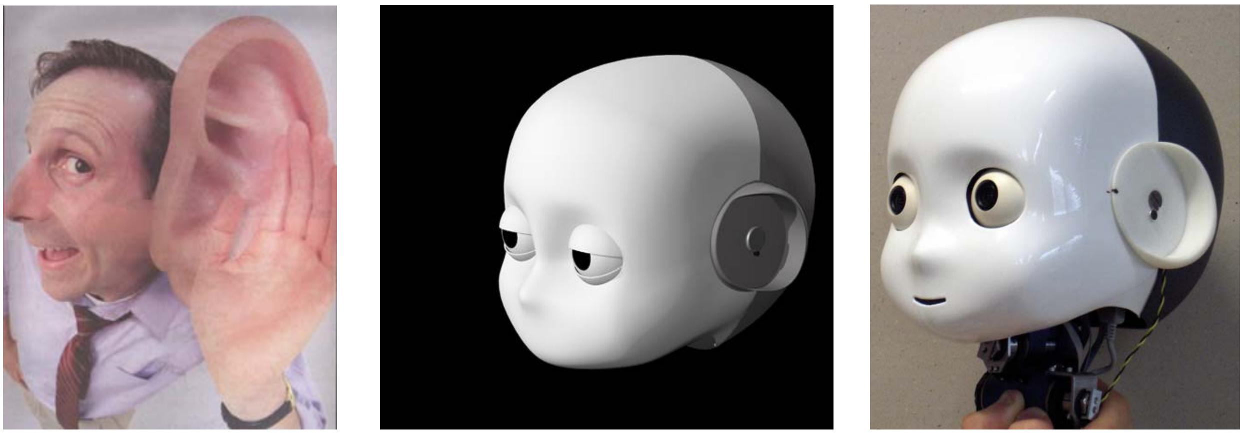
Left: Close-up view of the eyelid mechanism of the revised head. **Right:** the last and previous versions of the head.

As for the expressions, we have studied different expressions combining different shapes of the mouth and eyebrows. Preliminary versions were evaluated through tests with children (4-5 years of age) interacting with the robot. The children were asked if they thought a given face corresponded to an angry, surprised, happy, etc expression. This exercise led to modifications in the original designs and prototypes. More rounds of evaluation will be conducted in a more advanced stage of the prototype.



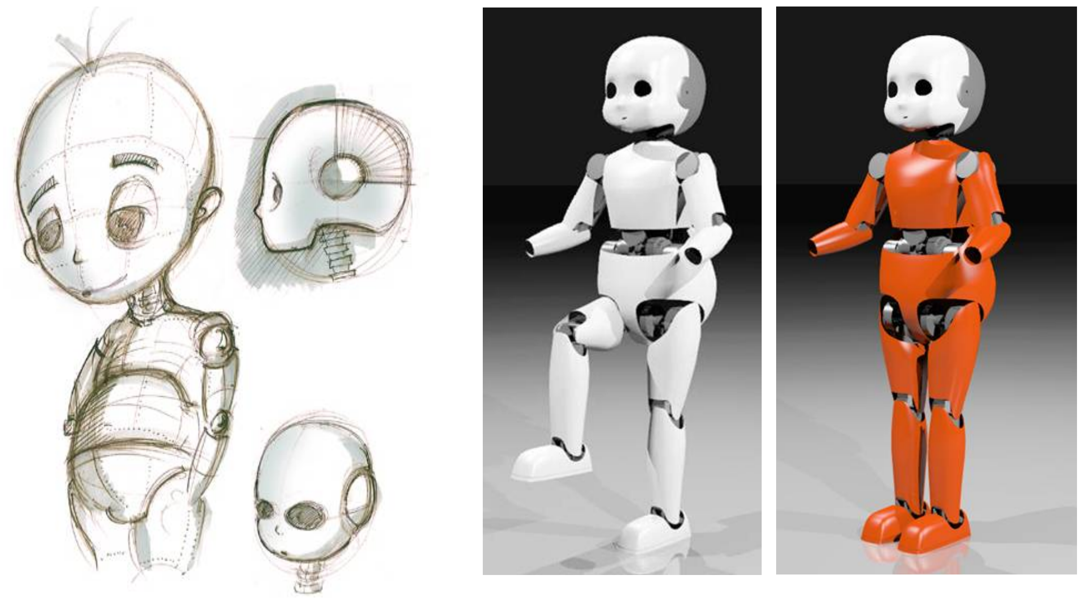
Left: Expressions obtained with LED panels. **Right:** On top the rendering of on expressions and the detail of the part generating the eyebrows illumination pattern.

During the second year of the project, IST worked on sound source localization from using a pair of microphones in the iCub head. The shape of the ears ***pinna*** was designed to allow for localization on the vertical plane (usually ambiguous). As a consequence of this design, the sound frequencies that are cancelled (frequency notches) depend on the microphone-pinna distance and therefore on elevation.



Left: Human ear ***pinna*** allows for vertical sound source localization. **Center:** CAD model of face with integrated ear design. **Right:** Prototype head with face/ear integration.

Another aspect that IST has studied, working together with the design company *Alma Design, inc* was the design of the body cover. So far, we have studied different concepts that were discussed within the consortium. The chosen version is shown in the picture below, which also includes the original concept study.



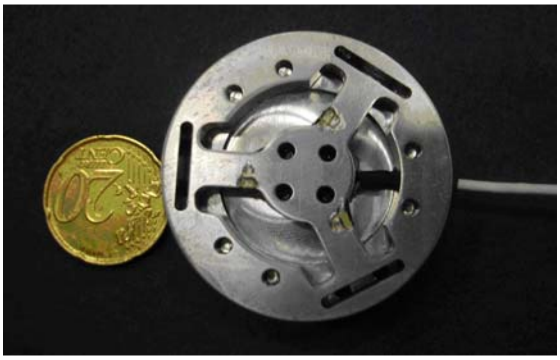
Left: Concept design for the iCub face and body cover. **Right:** model design of body cover.

UNISAL

Significant resources have been devoted by UNISAL to WP7 during the past reporting period and the following results have been achieved.

i). Legs, Hips and Spine Mechanical Design. The full design of the lower body has been completed and converted to the required drawing format for distribution as Open Source in line with the requirements of the consortium. Components have been sent out for fabrication with a due date of mid-May in line with timelines. Some components have been fabricated in-house for tolerance testing and control testing.

ii). Force Torque Sensor. A full 6 dof force torque sensor has been designed, fabricated and is currently under test. This sensor is an addition to the work programme at the outset. The goal is to produce high complexity sensing in each of the limbs in a package that his affordable.

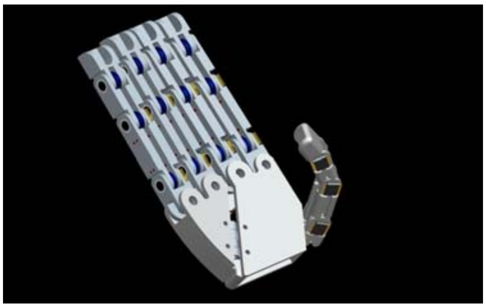


Force Torque Sensor

iii). A low resolution tactile skin has been designed for the lower body of the Cub. This activity has been undertaken earlier than expected but will be essential to the interaction capacity of the CUB. Some operational software has been produced for calibration and outline testing.

iv). A brief study of “skin” materials has been undertaken to identify polymer shells for the lower body. This may be of use and interested in the upper body designs.

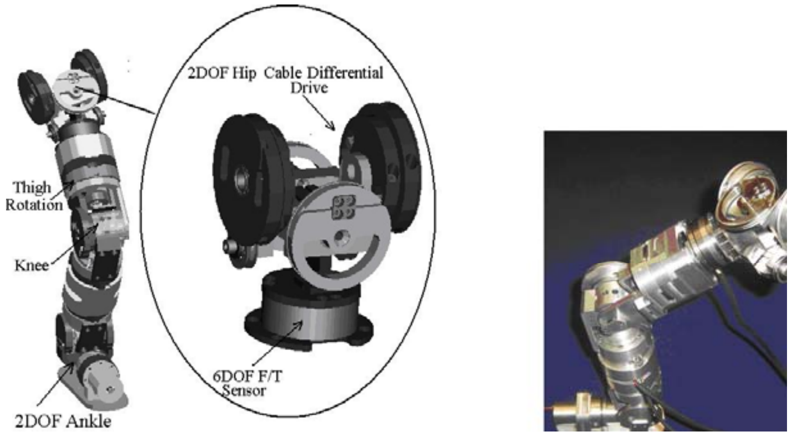
v). Based on our previous experience in the construction of robotic hand a baby hand has been designed to compliment the on-going activity. This system is studying new very compact joint sensing options that may be of use in other aspects of the project. At this stage a full CAD design has been produced. In addition a first finger has been machined and constructed for testing. Once these tests are complete the hand will be fully fabricated.



CAD design of a baby hand

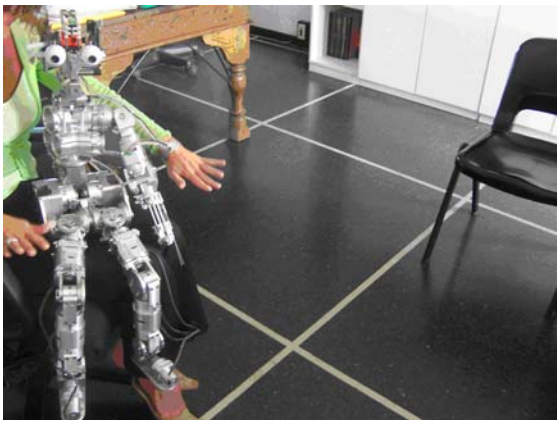
vi). An early hip spine assembly has been under test looking at the electronic drive systems and the control strategies. Data obtained in these trials will be used to inform the final hip spine controller.

vii). Full design construction and testing of the lower body of the iCUB



CAD model and mechanical realisation of the iCub leg.

viii). Integration and initial testing of the lower and upper body sections.



UNIZH

Kojiro Matsushita designed and manufactured a test bed for an active vision system, based on the iCub's design using the same motors and cameras (see Fig. 3g and 3h). He added angle sensors to the robot hand as well (See 3d). Gabriel Gomez prepared the electronics and the PID control for the active vision system (see Fig. 3g and 3h). Alejandro Hernandez added angle sensors to the humanoid head (see Fig 3e). We are waiting for quotes from Telerobot and Microdesign in order to build an iCub head for our lab. We have already ordered the iCub's motors and cameras. We continue the development of the robotic hand, the main changes between the first and the second prototype are depicted in table 1 (see WP2). Our current robotic setup consists in the following components: a robotic hand, an active color stereo vision system, a conventional robot arm, a robot arm with artificial muscles and some simulators.

Robotic hand

Our current prosthetic hand prototype has 13 DOF in total and consists of four fingers with 3 joints and 2 DOF each, one thumb with 2 joints and 3 DOF, and two additional DOF for the wrist. All the joints are actuated by tendon wires directly connected to a pair of servomotors, providing 2 DOF using the adaptive joint mechanism developed by (Ishikawa et al., 1999). The pressure sensors are placed on the fingertips, on the base of each finger and in the palm. Each finger has a flex/bend sensor and an angle sensor. The weight of our current prototype is 420 gm (1.2 kg including motors, sustaining structures for the motors, and tendons). A detailed model of the robotic hand (i.e., kinematics, position of sensors, pressure sensors) has been programmed within a realistic physics environment based in the open dynamics engine library (ODE) (see Fig. 3c and 3d).

Stereo color active vision system

A six DOF robotic head, each camera can be panned and tilted independently, the two additional DOF are for actuating the neck. The images from the cameras are recorded at a rate of 30 frames per second and a resolution of 320x240 (see Fig. 3b and 3e). Algorithms for visual processing (e.g., color detection, motion detection based on the optical flow, direction detection, log polar transformation, etc.) are already in place.

Conventional robot arm

An industrial robot manipulator (Mitsubishi® MELFA RV-2AJ) with five degrees of freedom (i.e., shoulder, elbow, and wrist) and a special connector to hold the robotic hand as illustrated in Fig. 3b.

Robotic arm with artificial muscles

Pneumatic systems offer great benefits concerning speed, weight and force. We have made some preliminary experiments to study ways in which the non-linear dynamics, redundancy, and compliance of the system can be exploited to achieve more natural kinds of movements. A first prototype built from FESTO pneumatic actuators is already available and an improved version is under construction (Fig. 3f).

Active vision system

We designed and manufactured a test bed for an active vision system based on the iCub's design using the same motors and cameras (Fig 3g and 3h).

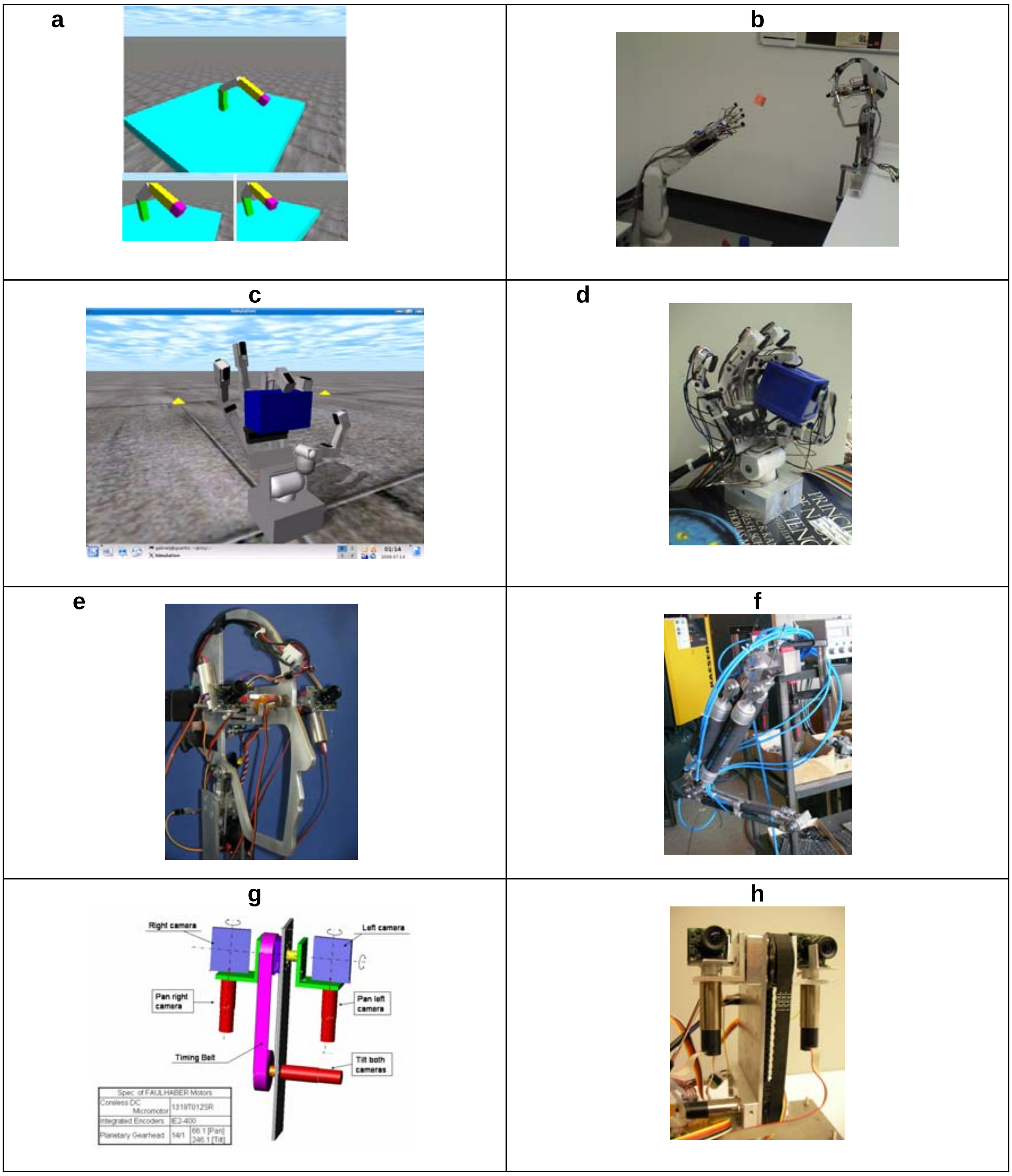


Figure 3 Illustrations of the different simulators and hardware platforms. (a) ODE simulation of the robot arm and the active vision system. The lower two images are from the perspective of the two cameras observing the robot arm (b) Complete robotic setup showing the active vision system, as well as the robotic hand mounted on the conventional robot arm, the robot is grasping and exploring an object using vision, tactile, and proprioceptive information (c) simulated hand interacting with a cube in the ODE physics environment (d) robotic hand interacting with a cube (e) humanoid head (f) first prototype of a quasi anthropomorphic pneumatic arm. (g) CAD design of new active vision system using the same motors and cameras as the iCub will have. (h) First prototype inspired in the iCub design.

SSSA

The main effort of SSSA has been focussed on the mechatronic design of a proto-type hand, based on technological limitations and manipulation requirements (see also Deliverable 7.2 - Analysis and pre-selection of the sensor's and actuator's technologies; M12). A mixed implementation of direct-driven joints and under-actuated joints (hybrid actuated finger) has been chosen. During the past 12 months, the final design of two approaches (the *totally under-actuated* and the *hybrid actuated)* of finger has been debugged and fixed. Complete details can be found in [Stellin et al. 2007], a copy of which is included in the collection of RobotCub papers. There follows a very brief summary of the current status of the design.

As shown in Fig. 1 and 2, the number of DoFs for each hand is 20. The number of DoMs is 9. Fig 3 shows an advanced prototype.

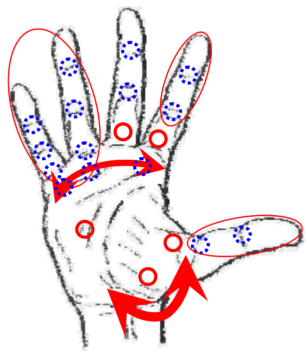


Fig. 1 The selection DoFs/DoMs in the hand

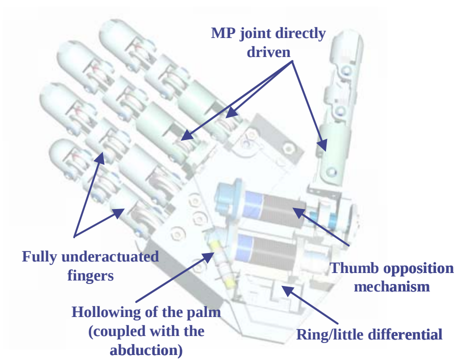


Fig. 2 The CAD drawing

Fig. 3 The prototype hand.

Finger	Length (mm)	Diameter (mm)	Range flection PIP,DIP, MP (°)	Range ab/adduction (°)
Index/Middle/Thumb	57	12	90	30 (only index)
Ring	57	12	90	30
Little	44	11	90	45

Table I: Dimensions and range of movement of the fingers

The hand is equipped with several sensors for control feedback and providing proprioceptive information. In particular it has:

- 12 hall-effect angular sensors. There is one for each flexion joint, except for the MP joint of index, thumb and middle.

- 2 optical proximity sensors. One for thumb opposition plane positioning, one for hollowing positioning.
- 5 cable tension sensors based on strain gages, one for each finger.
- 3 Torque sensory systems, based on hall-effect linear current sensors. One for each MP joint motor of thumb, index and little fingers.

All the motors dedicated to flexion of fingers have their own encoder for position control of the movement of the hand. Consequently, position information may be obtained by means of different sensors, i.e. both motor encoders and hall-effect sensors.

Deviations from the project work-programme

The mechanical design of the platform charged to Telerobot is higher than the initial forecast. The effort expended for Y2 will be consequently higher than initially estimated. The acquisition of four new employees in Telerobot allowed a redistribution of the planned activites with little delay on the planned schedule. Consequently the number of peoples in the effort table and their individual effort has changed from the initial forecast. Test and integration time of the first prototypes are longer than originally expected.

At UNISAL, additional unplanned work activity has been undertaken involving;
i). The development of the force-torque sensor
ii). The finger joint and sensing system
iii). The development of a potential format for a lower body skin and skin materials.

List of deliverables

Del. no.	Deliverable name	Workpackage no.	Date due	Actual/Forecast delivery date	Lead contractor
D 7.1	Specifications of the single components of the mechatronic platform with a preliminary integration compatibility analysis.	7	18, 30	24	TLR
D 7.2	Analysis and pre-selection of the sensor's and actuator's technologies.	7	12	12	SSSA
D 7.3	Experimental results of tests with existing platforms.	7	18, 30	24	UGDIST

List of milestones

Milestone no.	Milestone name	Workpackage no.	Date due	Actual/Forecast delivery date	Lead contractor

WP8 – Open System: iCub

Workpackage objectives

1. Define the activity related to the creation, licensing, and distribution of the "Open Platform".
2. Define the mechanical, documentation, and software standards to ensure the widest acceptability of the platform.
3. Help in defining the platform and coordinate with WP2 for requirements and WP7 for mechatronic and technological issues.

The activity of this Workpackage is devoted to the creation and support of the community of end-users of the open platform. At the outset, the main activity will be to define and establish the infrastructure of the RobotCub initiative. In this respect, the Workpackage will define the various standard and requirements.

The principal goal of this Workpackage is to maximize the likelihood that the open platform will become the platform of choice for research in embodied cognitive systems. Consequently, it is important to establish standards that will facilitate this adoption and foster the continued enhancement of the platform by the community at large, and the open sharing of these enhancements. The creation of an appropriate licensing strategy for the commercial and academic use of the platform is tightly bound up with this endeavor.

Progress towards objectives

UGDIST

In this period UGDIST has planned, designed, and released the open source software architecture (see http://yarp0.sf.net and http://eris.liralab.it/wiki/Deliverable_8.3)

UGDIST has also started the development of the embedded software.

TLR

In addition to the design activities reported in WP 7, TLR have also been involved in the specification of the open system, as follows:

- Reviewed and upgraded the documentation of the head and organized a series of copies made by different work shops in different countries to asses the validity of the documentation.
- Completed the documentation of the upper body;
- The review of the lower body documentation is scheduled from the beginning of October 06 (a copy of the lower body will then be replicated in Genova).

IST

As the developers of the iCUB head, IST has contributed to the definition of the documentation standards, mechanical design and components. The head CAD has been made available in the Robotcub repository.

In addition, during the second year of the project, IST has allocated a substantial effort to software development, according to the Yarp architecture. The implemented software (mostly related to vision and head control functions) has been used during the RobotCub summer school with the use of the IST prototype head.

UNISAL

As the Developers of the iCub lower body and one of the versions of the hand, UNISAL has worked in support of lead partners on the development of an open system. The particular activity has contributed to the development of a methodology for ensuring Open forms for the mechanical systems and definition of the documentation standards, mechanical design and components. The lower body CAD has been made available in the Robotcub repository.

Deviations from the project work-programme

Integration of imitation and communications skills anticipated in Milestone MY (below) by month 24 has not been achieved. This will be addressed in the coming period as the iCub becomes available for use by the partners.

List of deliverables

Del. no.	Deliverable name	Workpackage no.	Date due	Actual/Forecast delivery date	Lead contractor
D 8.1	Initial Specification of the CUB Open System.	8	12, 30	12	UGDIST
D 8.2	Definition of Documentation and Manufacturing Procedures.	8	12, 30	12	UGDIST
D 8.3	Software Architecture	8	18, 30	24	UGDIST

List of milestones

Milestone no.	Milestone name	Workpackage no.	Date due	Actual/Forecast delivery date	Lead contractor
MY	General sketch of the full humanoid, not yet executive drawings Initial integration of some imitation and communication skills	8	24	24	UGDIST

WP9 – Community Building and Self Assessment

Workpackage objectives

1. Extend the base of knowledge for the definition of the CUB cognitive and mechatronic architectures and the adopted technologies by co-opting EU and non-EU scientists.
2. Promote an international project on Embodied Cognition supported by national and international funding agencies.
3. Monitor the advancement of the project toward the fulfillment of the project's objectives.
4. Organize training and dissemination activities.

The work in this WP is mostly related to organization of meetings and workshops to reach the four objectives described above. The meetings will be organized as internal or open to the scientific and industrial communities. The management bodies relevant for this Workpackage are the International Research Panel (IRP) and the Board of Management (BM). Jointly they will decide on the topics to be discussed and the format of the meeting. The members of the IRP will be responsible of contacting funding agencies that may be interested in joining the International Project as well as industrial organizations potentially interested in monitoring the results of RobotCub.

Progress towards objectives

UGDIST

The RobotCub website has been completely redesigned and a new RobotCub Wiki has been added.

Significant effort went into organizing the 1st RobotCub summer school; see http://www.robotcub.org/summeschool. The summer school was attended by 32 students and focussed on using the new Yarp-based software architecture (http://yarp0.sf.net and http://eris.liralab.it/wiki/Deliverable_8.3) to interact with and control two humanoid robots (James and the iCub).

Internationalization activities continue mainly through the good offices of our International Research Panel and through on-going advertisement of the iCub and the RobotCub project (e.g. at the Commission's FP7 Planning Workshop on Models and Paradigms: http://cordis.europa.eu/ist/cognition/presentations.htm). At present, however, we are somewhat cautious about raising the profile of the iCub too much until there is minimal risk associated with the delivery of a fully-functional robot, i.e. until we get closer to the date of the open call for participation and the launch of the successful projects that result from the call. To that end, we are deferring the report on internationalization activities until M36 to coincide with the launch of the open call. A task to prepare for this launch has been added to the Detailed Implementation Plan M25-M42.

IST

Last year, IST organized a competition for high school, Art and Design students for the design of the iCub face and expressions. This procedure had an enthusiastic response from the students and results were documented in the review meeting. This year, IST took the robot head prototype, including the preliminary version of the body cover (no moving joints) to a kinder garden. The experience served to assess the interaction between children and the robotic platform as well as for testing the expressions. Several demos were run with the help of the children.

Left: iCub head with prototype of body cover (no moving joints in the body). **Right:** interaction tests in a kinder garden.

UNISAL

UNISAL worked in promoting the project to the community and in particularly forming links with psychologists to permit insights into the needs of cross-disciplinary work in the area of cognition, child psychology and robotics.

Deviations from the project work-programme

D 9.3 deferred from M18 to M36.

List of deliverables

Del. no.	Deliverable name	Workpackage no.	Date due	Actual/Forecast delivery date	Lead contractor
D 9.1	Proceedings of the Initial Scientific Meeting.	9	6	6	UGDIST
D 9.2	Material produced for the training activities.	9	18	24	UGDIST
D 9.3	Progress report on Internationalization activities.	9	18	36	UGDIST

List of milestones

Milest one. no.	Milestone name	Workpackage no.	Date due	Actual/Forecast delivery date	Lead contractor
-	-	-	-	-	-

Section 3 – Consortium management

Change in Project Manager

Owing to unforeseen and significant new demands on his time due to his appointment as Director of Research at the newly-established Italian Institute of Technology, Giulio Sandini handed over responsibility for day-to-day project management of RobotCub to David Vernon on the 23rd August 2006, with Giorgio Metta continuing to focus on the iCub platform and software architecture. David Vernon will still be responsible of the cognitive architecture aspects of the project. Giulio Sandini in his role in the IIT will continue to support the project for example by providing space, tools and support for the construction of the iCub platforms and the establishment of the Research and Training Site.

Change in Primary Contact Person

On the 4th October, Prof. Paolo Dario formally handed over the role of primary contact person for Scuola Superiore Sant'Anna to Prof. Cecilia Laschi. Prof. Laschi will henceforth be the person responsible for all SSSA activities on the RobotCub Project and will be the SSSA representative on the Board of Management.

Coordination of and Collaboration among Partners

The management of a large consortium and the establishment strong collaborative links is a significant challenge. There is always a tension between partners caused by the need and desire to work on specific aspects of the project for which they accepted responsibility at the outset and the need that emerges as the project evolves to work on other aspects for the common good of the project. We mention one specific manifestation of this in the next section on Software Development. While there are several instances of strong collaboration on the design and fabrication of the iCub (UGDIST/UNISAL/IST/TLR) and also significant bi-lateral collaboration on cognitive issues (e.g. EPFL/UNIHER, EPFL/UNIFE, UNIFE/UNIUP, UNIHER/UNIFE), there has been less success in establishing strong collaboration on the overall problem of modeling cognitive processes. The re-worked version of D2.1 A Roadmap for the Development of Cognitive Capabilities in Humanoid Robots has been one of the main driving forces for such general project-wide collaboration, initially in the identification of phylogenetic capabilities and ontogenetic processes, and latterly in the development of the iCub Cognitive Architecture. Unfortunately, a significant amount of work remains to be done to engender strong multi-party collaboration on this crucial area. What can be said on this is that we have established the base requirements for the cognitive architecture as well as having created an initial paper design, in addition to the important creation of a sound operational software architecture based on the Yarp system. It remains to build on this and get the commitment of partners to writing the software that will comprise the cognitive architecture.

Software Development

It is now clear that more partners need to contribute to the development of software for the iCub. It was agreed at the project meeting on the 19 July 2006 that the focus initially should be on the phylogenetic abilities in the Detailed Implementation Plan M25-M42. Unfortunately, and notwithstanding the good will that they express, many if not most of the partners in the consortium are focussed on their own particular areas of research. At present, the lion's share of this work is falling to UGDIST and IST. Of course it doesn't help that an iCub isn't yet available to the partners to facilitate this development. This is an inevitable problem with the timing of the project and to an extent this is being alleviated by the new approach we have adopted in releasing iCub sub-systems progressively (see Section 1: Review Recommendations and Consequent Actions). It should be noted that where possible, some partners have at least undertaken to make critical parts of their work compatible with the Yarp-based iCub Software Architecture. This has been reflected explicitly in the new Detailed Implementation Plan M25-M42. Nonetheless, significant new commitment is required if we are to achieve our goal of creating a self-contained cognitive humanoid robot.

Re-structuring of Certain Deliverables

We made a strategic decision in August to issue four deliverables, not as paper documents, but as on-line documents on the newly-developed RobotCub Wiki (http://eris.liralab.it/wiki/Main_Page).

1. D7.1 Specifications of the single components of the mechatronic platform with a preliminary integration compatibility analysis
2. D8.3 Software Architecture
3. D9.2 Material produced for the training activities
4. D9.3 Progress on internationalization activities

This decision was made on the basis that these deliverable are all very dynamic and require constant updating by several parties. It was felt that this can be most easily effected using the collaborative development environment of a Wiki.

With the exception of D9.3, a formal paper deliverable has been be produced which simply provides a link to the Wiki page. D9.3 has been deferred to Month 36 to coincide with the launch of the open call for new research proposals.

International Research Panel (IRP)

The IRP meeting scheduled for October 2006 is to be postponed until October 2007.

Personnel

UGDIST intend to recruit an engineer or technician to assist Giorgio Metta with on-line documentation, component ordering & follow-up, etc. UGDIST also intend to recruit an engineer to work directly with TLR on the fabrication of the iCub and a software engineer to look after the software integration, documentation, and distribution.

Timing of Open Call

We have now agreed a timetable for the open call for participation by third parties. This is set out in the Detailed Implementation Plan M25-M42 but for convenience we note it again here:

Month 30: Open call task begins
Month 36: Launch of competitive call for proposals
Month 40: Announcement of successful proposals
Month 42: Launch of new projects: deployment of iCub kits & version1 of iCub software

In addition, the creation of a Research and Training Site (RTS) will be scheduled as follows.

Month 30: RTS task begins
Month 36: Creation of the RTS

The plan is for the those whose research proposals are successful will spend a number of months in Genova at the RTS working on the assembly of the iCub kit, beginning at month 42.

Ancillary Activities

Although the following activities also fall under the heading of WP8 on building an iCub community, it is worth emphasizing them again here since they required a considerable amount of coordination effort. These include

- Helping EPFL, UNIZH, and IIT with the realization of the copy of the head
- Re-vamping of the RobotCub website
- Creation of a CVS software repository
- Creation of a RobotCub Wiki
- Organization of the 1st RobotCub summer-school

Domain Names

The consortium has acquired the rights to the robotcub.eu and icub.eu domain names. We continue to use the .org versions in our day-to-day work as it conveys a disposition that is more open to international and intercontinental involvement.

“RobotCub” and “iCub” are now registered trademarks of the prime contractor, acting on behalf of the consortium.

Press Release

A revised press release has been issued.

List of Conference Papers and Journal Publications

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Section 4 – Other issues

None.

ANNEX – Plan for using and disseminating knowledge

Section 1 – Exploitable Knowledge and its Use

The RobotCub project is dedicated to the production of free-available open source results license under the GNU General Public Licence. Consequently, direct commercial exploitation is precluded.

Section 2 – Dissemination of Knowledge

Publications

See Section 3.

Dissemination Activities

- Robot demonstrations and poster presentations of RobotCub project at RO-MAN2006. This included interviews with regional and national television and national radio stations. (Anglia TV, Sky Broadcasting, Radio 4).
- N.A Mirza gave an invited talk at ASCS2006 (The Third International Seminar on Applied Analysis and Synthesis of Complex Systems) held on June 29/30, 2006 at IIASA (International Institute for Applied Systems Analysis), Laxenburg, Austria. Organised by Kyoto University. The talk highlighted the RobotCub project and the research work on Interaction Histories.
- Conference presentation at ICDL (International Conference on Development and Learning), Bloomington, Indiana, USA, 2006. (Interaction Histories)
- Conference presentation at the 5th International Conference on Epigenetic Robotics, Paris, France, 2006. (Interaction Histories)
- Conference presentation at RO-MAN2006, University of Hertfordshire, Hatfield, UK. (Robot Design and Perception of Robot Expressions)
- C.L. Nehaniv gave an invited talk at the 50th Anniversary Summit on Artificial Intelligence, Monte Verita, Switzerland (July 2006)
- Kerstin Dautenhahn gave an invited talk at the 50th Anniversary Summit on Artificial Intelligence, Monte Verita, Switzerland (July 2006).
- C.L. Nehaniv gave an invited presentation at the NSF/EPSRC International Workshop on Cognitive Robotics, Intelligence and Control, Windsor Park, UK (August 2006)
- C.L. Nehaniv gave an invited talk at the Norwegian University of Science and Technology (NTNU), Trondheim, Norway (August 2006)
- Lars. A. Olsson successfully defended and has been awarded his PhD at the University of Hertfordshire for his research related to RobotCub:
  Lars A. Olsson, Information Self-structuring for Developmental Robotics: Organization, Adaptation, and Integration, PhD thesis, University of Hertfordshire, May 2006
- Presented L. Olsson, C. L. Nehaniv, & D. Polani, "Measuring Informational Distances Between Sensors and Sensor Integration", Tenth Conference on Artificial Life, Blooimington, Indiana, June 2006.
- Giulio Sandini, Giorgio Metta, and David Vernon gave a talk at AI50, Monte Verita, Switzerland (July 2006)

- Giulio Sandini, Giorgio Metta, and David Vernon gave three talks at the XXV Scuola Annuale, Neuro-Robotic: Neuroscienze e Robotica per lo sviluppo di macchine intelligenti, Bressanone, Italy (September 2006)
- Giorgio Metta and Paul Fitzpatrick organized the first RobotCub Summer School, Ventimiglia, Italy (July 2006)
- Giorgio Metta and Giulio Sandini presented a poster at the Inaugural Meeting of euCognition, Nice, France (February 2006).
- Giorgio Metta, "Why development matters" invited talk at the ICDL06 conference in Bloomigton, IN, 30th May-2nd June 2006
- Giorgio Metta "Making use of sensory information in robotics" invited lecture at the Neurobotics Summer School in Umea, Sweden, 21-25th Aug, 2006
- Giorgio Metta "Development and robotics" invited lecture at the CoSy Summer School in Berlin, Germany, 19-22nd Sept, 2006
- IST: Visão (popular portuguese newsmagazine), September 14th 2006.
- IST: Visit of the Vice-Minister for education of the People's Republic of China.

During the visit to IST of the Vice-Minister for Education of the People's Republic of China, Mrs. Wu Quidi, there was the opportunity to describe the RobotCub project and show the various robotic platforms (Baltazar and the different versions of the iCub head). (September 2006)

- Swiss Television ("10 vor 10"), one of the most popular newscasts in Switzerland made an interview with Rolf Pfeifer and they filmed a demonstration of the humanoid head and the tendon driven robotic hand grasping different objects.

- Künstliches Kind im Laufgitter. Computerworld, pp. 52.

- Alexander Schmitz gave a radio interview to the Austrian (ORF) channel on the 20th of February, 2006.

- Roboter in der Krabbelstube. Spiegel, 24 December 2005, pp. 154-155.

- Gabriel Gomez gave an invited talk at the Tweak fest (a science and art fair) in Zurich on November 10th, 2005 about RobotCub project and the ongoing work with the robotic hand.

- Talk: „Die robotisierte Menschen Hand".

- A movie describing work conducted by EPFL-A as part of WP3 and WP5 is available at: http://lasa.epfl.ch/videos/control.php entitled *Dynamical Visuo-motor control* This video relates [HerschGuenterCalinonBillard06].

- A web page describing the crawling of the iCub is available here: http://birg.epfl.ch/page63115.html

- See also the following page for work and movies by EPFL-B on biped locomotion control: http://birg.epfl.ch/page56604.html

- 3-5 min segment on "The Gadget Show", Channel 4, UK Jan 2006

- Finger tracker – part of project winning best exhibit/demo at Virtual Concepts 2005, Biarritz, France, Nov. 2005.

Section 3 – Publishable Results

None at this point.