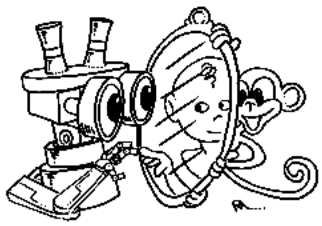

MIRROR

IST–2000-28159

Mirror Neurons based Object Recognition

Deliverable Item 1.4
Periodic Progress Report N°: 1

Covering period 1.9.2001-31.8.2002

Delivery Date: November 15th, 2002

Classification: Internal

Responsible Person: Prof. Giulio Sandini – University of Genova

Partners Contributed: ALL

Contract Start Date: September 1st, 2001 Duration: 30 Months

Project Coordinator and Partners:

DIST - University of Genova (Prof. Giulio Sandini and Dr. Giorgio Metta)

Department of Biomedical Sciences University of Ferrara (Prof. Luciano Fadiga)

Department of Psychology – University of Uppsala (Prof. Claes von Hofsten)

Istituto Superior Tecnico – Computer Vision Lab – Lisbon (Prof. Jose Santos-Victor)

information society technologies

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Content list

1. Executive Summary

In the first year our main objective was to find a common framework to address, with our different methodologies, the main scientific question of the project namely how the mirror system develops. For this reason we had to both implement/update our respective experimental setups and to define common experimental paradigms. More specifically the first year's main objectives were:

1) To realize the experimental setups required for jointly addressing the relevant scientific issues;
2) To start individual pilot studies whose results will be used to define the activities for the next year.

As to point 1) the following setups have been realized:

a) Setup for the acquisition of visual and motor data from human subjects during grasping actions (see Deliverables 3.1 – 3.2 and 3.3).
b) Setup for the acquisition of single neuron data from behaving monkeys during grasping (see Deliverables 4.1).
c) Setup for the acquisition of grasping data from infants (Deliverables 4.2).
d) Robot hand for the implementation of the robotic model (Deliverable 2.1 and 2.2).

As to point 2) above the following pilot studies have been performed:

a) Modeling of "posting task" learning with the robotic set up (Deliverable 2.1 and 2.2).
b) Initial experiments with infants engaged in grasping a "rotating rod" (Deliverable 4.4).
c) Initial recording from single neurons of behaving monkeys in various conditions characterized by changing the visual feedback (Deliverable 4.3).
d) Initial experiments with imitation learning (Deliverable 2.3).

According to our original plans the setups are now fully functional and the outline of the second year's activities is clearer. Our main goals for the second year are to investigate: i) how visual and motor information can be used to learn to discriminate grasping actions *by looking*; ii) the role of visual feedback in the ontogenesis of mirror neurons in monkeys; iii) the temporal sequence of the emergence of manipulative skills in human infants.

Cooperation among the partners is well established and lead to a conspicuous exchange of information and know-how also outside the specific goals of the project. Effort and funding are being used as planned apart from minor changes.

The review report consists of:

1) This document and the accompanying CD-Rom containing some videos of the experiments and the setup realized in the first year.
2) A draft document outlining our working hypothesis of the model of mirror neurons.

2. First year activities

The goals of MIRROR are: 1) to realize an artificial system that learns to communicate with humans by means of body gestures and 2) to study the mechanisms used by the brain to learn and represent gestures. The biological base is the existence in primates' premotor cortex of a motor resonant system, called mirror neurons, activated both during execution of goal directed actions and during observation of similar actions performed by others. This unified representation may subserve the learning of goal directed actions during development and the recognition of motor acts, when visually perceived. In MIRROR we investigate this ontogenetic pathway in two ways: 1) by realizing a system that learns to move AND to understand movements on the basis of the visually perceived motion and the associated motor commands and 2) by correlated electrophysiological experiments. `(From MIRROR's Technical Annex)`

The first year activity of MIRROR has been formally reported in the deliverables listed in the following table:

DELIVERABLES TABLE

Project Number: IST-2000-28159

Project Acronym: MIRROR

Title: Mirror Neurons Based Object Recognition

Del. No.	Title	Leader	Type	Classifi-cation	Due
1.1	Project Presentation	DIST	Web Report	Public	1
1.3	Management Report 1	DIST	Report	Public	6
2.1 – 2.2	Robot setup	DIST	Report	Public	6
2.3	Visual primitives for object identification	IST	Software	Public	8
2.4	Basic robot behaviors	IST	Demo	Public	12
3.1	Biological data acquisition setup specifications	UNIFE	Report	Public	6
3.2 – 3.3	Biological data acquisition setup Data collection analysis and processing software	IST	Prototype	Public	8
4.1	Protocol for the monkey experiments	UNIFE	Report	Public	6
4.2	Protocol for the behavior development experiments	UU	Report	Public	6
4.3	Preliminary results of the monkey experiments	UNIFE	Report	Public	12
4.4	Preliminary results of the behavior development experiments	UU	Report	Public	12

2.1. Workpackage 1 – Management and Coordination

The mirror project started the first of September 2001 with a consortium composed of four partners.

The research activity was initiated without delays with a **kick-off meeting** that was held in Genova on September 7-8. The meeting was attended by all partners. The kick-off meeting objectives were two: 1) update the mutual knowledge about the scientific activities of the partners; 2) plan in more details the initial steps of the project.

The **second meeting** was scheduled at month six and was held in Lisbon. All partners attended the meeting. The main objective of this meeting was to report the activities of the first six months and to plan activities for the next months.

During the management part of the meeting documents describing the procedures and format for the preparation of the first year report and the cost-statement (both due in September) were presented.

The **third meeting** was held in Ferrara on October 18-19th. At this meeting the results of the first year activities were presented and the attendance and program of the review meeting was discussed.

The fourth meeting has been scheduled to take place in May in Uppsala.

Besides these formal meetings the cooperation during this initial phase of the project went on particularly through e-mails, phone calls, and technical meetings. The major issues discussed were related to the different experimental setups being implemented at the different laboratories. Discussions about joint experiments were also very interesting both before and during the discussion periods of both the kick-off as well as the Lisbon meeting.

The research activity is proceeding as planned with some changes as detailed in the individual reports here.

2.1.1. Activity at DIST - University of Genova

The research activity at DIST has been mainly devoted to the design and implementation of the biological data acquisition and of the robot setup. These activities are reported in details in deliverables 2.1 and 3.1. In summary, the setup for biological data acquisition composed of a data-glove and a pair of stereo cameras is now completed. The robotic setup is also completed as the robot hand was delivered at the end of October. A **change with respect to the original plan** is that we decided to proceed first with the realization of the robot's hand and afterward, resources allowing, with the realization of the arm. As to the robot arm the decision to postpone its realization is motivated by the fact that the tests we performed on elastic actuation are still not completed and at this stage we do not have enough confidence about their use in a complete robot arm. The reason for this is the fact that we would like to be able to control a somewhat large range of stiffness and therefore we need to test different mechanical arrangements (e.g. springs with different elastic constants and number of turns). Besides the realization of the two setups we started some specific experiments on "learning to act" in parallel with similar experiments performed by the group at University of Uppsala on young infants.

References

L. Natale, S. Rao, G. Sandini. *Learning to act on objects. 2nd Workshop on Biologically Motivated Computer Vision (BMCV).* Tübingen (Germany), November 22-24, 2002

G. Metta and P. Fitzpatrick. *Early integration of vision and manipulation.* Submitted to Adaptive Behavior, a special issue on Epigenetic Robotics. October 2002

G.Metta, L.Natale, S.Rao, G.Sandini. Development of the "mirror system": a computational model. In Conference on Brain Development and Cognition in Human Infants. Emergence of Social Communication: Hands, Eyes, Ears, Mouths. Acquafredda di Maratea - Napoli. June 7-12, 2002.

L. Natale, G. Metta, and G. Sandini. Development of Auditory-evoked Reflexes: Visuo-acoustic Cues Integration in a Binocular Head. Robotics and Autonomous Systems, vol. 39/2 pp. 87-106, 2002.

Paul Fitzpatrick, Giorgio Metta, Lorenzo Natale, Sajit Rao, Giulio Sandini. What am I doing? Initial steps toward artificial cognition. (Submitted to IEEE Conference on Robotics and Automation)

2.1.2. Activity at DBS – University of Ferrara

During the first year, the UNIFE-DBS activity was mainly addressed to: (1) setting up the monkey experimental paradigm and starting with neuron recordings and, (2) in collaboration with DIST, setting up the biological data acquisition system. In addition to these two main streams, we **added a modification** to our original plan consisting in (3) some new experiments inspired by our recent finding that a motor resonance, similar to that observed in monkey mirror neurons, can be evoked not only by action viewing but also when a subject is passively listening verbal stimuli acoustically presented.

More in detail, (1) concerning monkey experiments, we devoted a large effort to improve recording conditions, in terms of both the animal well-being and the overall technical quality. Details regarding these improvements can be found in Deliverable 4.1. The to-be-recorded monkey was then trained to interact with experimenters and to perform the task according to the experimental paradigm. Finally, we electrophysiologically mapped the frontal cortex in order to delimitate the region of interest (area F5) by establishing the borders with neighboring areas (FEF, rostrally and F4, caudally). (2) The biological data acquisition system is now described in Deliverables 3.1, 3.2 and 3.3. (3) In the framework of the investigation of speech-related acoustic mirror effect, we are testing whether the motor resonance induced by speech listening represents a mere epiphenomenon or if it reflects an involvement of motor centers in speech perception (as suggested by the famous Liberman's theory of speech perception). With this aim we are both psychophysically investigating the phonological representation of speech and electrophysiologically studying the human Broca's region by using a specially designed Transcranial Magnetic Stimulation (TMS) paradigm. A more detailed description of this task will be given in Deviation from planned activities Section of this document.

2.1.3. Activity at ISR – Instituto Superior Tecnico in Lisbon

In addition to the regular activities of the project (meetings communication, etc) during the first year of MIRROR, IST has worked primarily in *WP2 – Artifact Realization* and in WP3 – *Biological Setup*.

The work developed in WP2 consisted in several components. We have studied the problem of imitation of human gestures by an artifact. The approach considers a Sensory Motor Map, that links the control of the posture of the arm with the corresponding visual observations and a View Point Transformation which needs to be performed to align the demonstrator's gestures and the artifacts ego-image (as if looking at its own arm). This work is described in detail in DI-2.3 even if some of its contents correspond to Task T2.6 that was originally planned for the second year of the project. Also in WP 2, we have proposed a methodology that allows the computation of dense disparity maps from stereo pairs of log-polar images. In addition, IST has developed several low-level visual primitives (e.g. corner detection, normal flow estimation, and tracking) that shall be used later in the project.

Finally, in WP3 IST participated together with DIST in the discussion regarding the definition of the experimental setup (DI-3.1). Based on the available data, IST will apply some of the developed methods to the acquired images in order to assess the quality and significance of different visual primitives for the purpose of object recognition or action categorization. Preliminary steps in this direction (with images in real, unconstrained scenarios) have been explored in WP2.

IST has also collaborated with University of Ferrara for the definition of the setup for stereo acquisition of the neuroscience experiment and it is planned to further develop this collaboration in the future.

The work done by IST in the context of MIRROR has led to several technical reports and to a paper to be presented at the Workshop of Biologically Motivated Computer Vision to be held in Tubingen, Germany, in November 2002.

2.1.4. Activity at DP – University of Uppsala

During the first year of the project, UU has worked on two kinds of experimental paradigms investigating young children's prospective control of hand adjustments in manual tasks. In the first paradigm, infants' ability to adjust hand orientation when grasping a rotating rod has been studied. One set of experiments has been completed and is currently being written up. Three groups of subject were included: 6-month-olds, 10-month-olds, and adults. The rod, the target of reaching, was either stationary or rotating at 18 or 36 deg./s. Reaching movements were measured at 240 Hz with 5 cameras registering the 3-D position of passive reflective markers placed on the hands and the object. The results show that reaching movements are adjusted to the rotating rod in a prospective way and that the rotating rod affects the grasping but not the approach of the rod. In the second paradigm, young children's ability to adjust the orientation of objects with various shapes in order to fit them into holes is studied. The experiments utilize the natural interest of young children in fitting objects into holes. By varying the form of the objects and the holes, the difficulty of the task can be manipulated. Pre-adjustments of the orientation of the various objects before trying to push them through the holes, give information about the subjects spatial cognition as well as their ability to plan these actions. Some experiments have been completed an others are planned. In addition to these manual tasks, UU has proceeded with its work on the development of predictive visual tracking. Infants' ability to smoothly track objects of different size, track them along different trajectories, and over occlusion has been studied.

References:

1. Achard, B. and von Hofsten, C. (2002) Development of Infants' ability to feed themselves through an aperture. **Infant and Child Development**, **11**, 43-56..
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4. Witherinton, D.C., von Hofsten, C., Rosander, K., Robinette,A., Wollacott, M.H., and Bertenthal, B.I (in press) The development of anticipatory postural adjustments in infancy. **Infancy.**

5. Gredebäck, G., von Hofsten, C. and Boudreau, P. (2002) Infants' tracking of continuous circular motion and circular motion interrupted by occlusion. **Infant Behavior and Development,** in press.

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7. Bäckman, L. and von Hofsten, C. (Eds.) (2002). **Psychology at the Turn of the Millennium: Volume 1: Cognitive, Biological, and Health Perspectives.** London: Psychology press.

8. von Hofsten, C. and Bäckman, L. (Eds.) (2002). **Psychology at the Turn of the Millennium: Volume 2: Social, Developmental, and Clinical Perspectives.** London: Psychology press.

9. von Hofsten, C. (in press) Development of prehension. In B. Hopkins (Ed.) **Cambridge Encyclopedia of Child Development**.

2.2. Workpackage 2 – Artifact

2.2.1. Deliverables 2.1 and 2.2 – Robot Setup

These Deliverables describe the work we carried out with the robotics setups. This activity has been divided in two parts: the design and realization of a robot hand and the execution of some preliminary experiments of reaching/grasping. The initial plans were to design a whole arm-hand system, however, we decided to concentrate our effort on the design of a robot hand because, on one side, it represents the main "tool" for addressing grasping issues and, on the other, we estimated that our current robot arm is perhaps sufficient for the goals of the project.

Robot Hand

The main specifications of the robot hand are:

1. Shape as much as possible similar to a human hand. This is particularly important for Mirror because we want to design a tool, which, not only moves like a human hand, but also looks like a human hand. We want to test how our system learns to discriminate between different grasps "simply" by looking at the hand during execution of the grasp. For this reason we opted for a 5-finger hand of about the same size of a human hand.
2. Enough degrees of freedom to allow the generation of, at least, three different grasp types. To allow different grasp types to be performed without controlling unnecessary degrees of freedom, we opted for a kinematic configuration where 16 joints are controlled by "just" six motors and the redundancy is managed by elastic couplings (springs) between some of the joints. The six actuators are assigned so that two of them control the thumb, two the index finger and the last two are used to control the last three fingers.
3. Rich sensory information; Because of the elastic couplings of some of the joints, position sensors (Hall effect sensors) have been included in all 16 degrees of freedom. This should allow measuring position and torque on all joints (by exploiting the combination of the encoders and the Hall effect sensors).

Figure 1 presents the CAD design of the robot hand (panel A, B, and C) in a few grasping configurations and a picture of the actual hand. Panel D shows the index finger of the robot hand compared to the size of a human hand.

A B C

D E F

Figure 1: Robot hand. The hand was designed in collaboration with CM Ingegneria and TELEROBOT S.r.l.

2.2.2. Deliverable 2.3 – Visual primitives for object identification

Important aspects of the mirror system we want to investigate are:

- The mapping mechanism required to transform one's motion parameters into motion parameters of a "mirrored" actor.
- The role of object's shape in the learning and interpretation of grasping actions.
- The relevance of global motion parameters in the identification of grasping.

This deliverable describes the software package being implemented for the visual primitives required by the artifact. In more detail, this deliverable describes:

i) A methodology developed for computing the view point transformation between the artifact's own arm and the demonstrators when performing imitation. Even if this is a high level behavior that exceeds the scope of this description, it also includes processes for hand/arm segmentation in video sequences. See Figure 2 for an example.

ii) An approach for the computation of 3D dense depth maps from binocular disparity channels using log-polar images; see Figure 3.

iii) Low-level processes and software for extracting image corners and compute the normal flow from image sequences.

These visual primitives will be integrated in the final artifact at a later stage of the project.

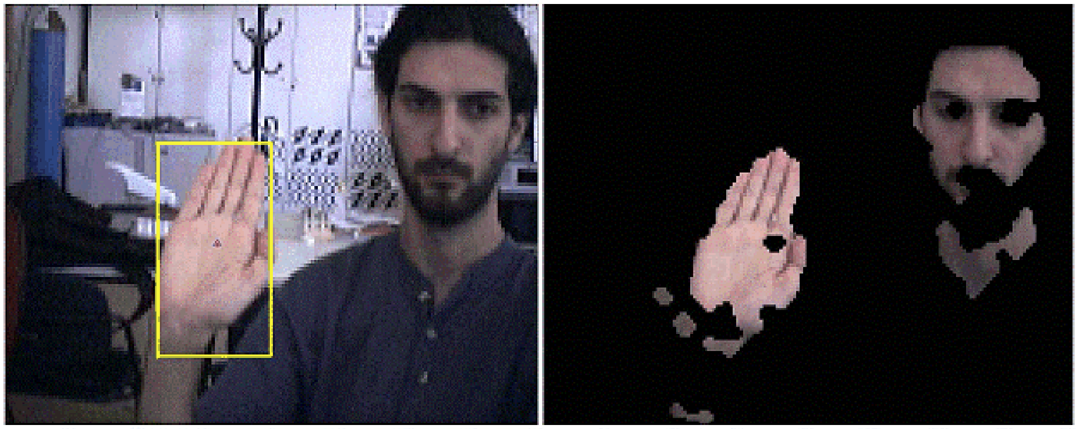


Figure 2: Extraction of visual data relevant for imitation learning. The hand is segmented on the basis of color information.

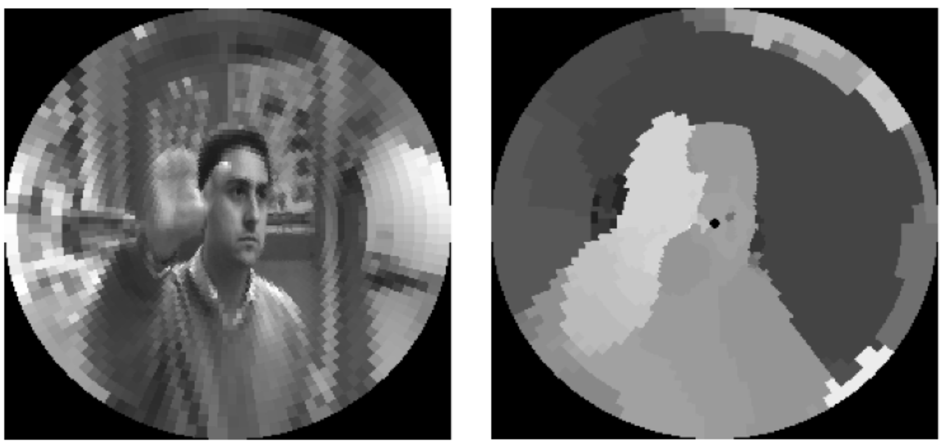


Figure 3 The picture above shows an example of one of the input images and the estimated disparity map.

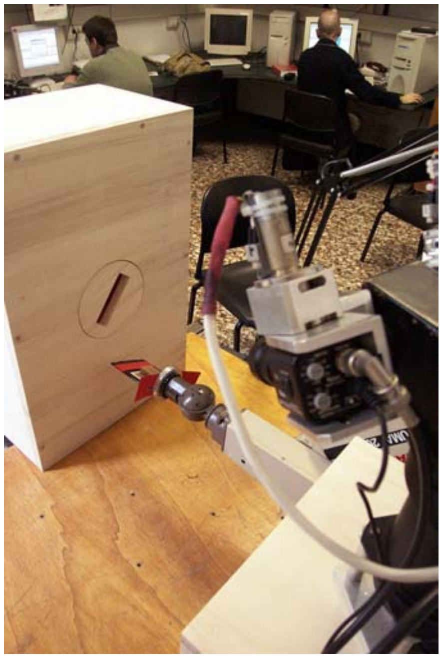
2.2.3. Deliverable 2.4 – Basic robot behaviors

This deliverable consists of a collection of videos detailing, among other things the basic behaviors implemented during the first year. The most important are the so-called “posting experiment” and the “learning to push” behavior.

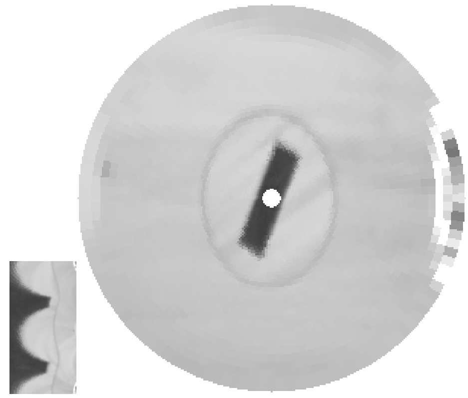
Robot’s “posting” experiment

During the first year the robot hand was not available. On the other hand we wanted to start addressing the “grasping issue” from the modeling point of view and for this reason we decided to perform two experiments. The first one, which we called the “posting” experiment, involves the control of the orientation of the hand. The robot has to learn the correspondence between the orientation of a visually identified “slit” and the correct orientation of the “hand”. The rationale being that the orientation of the hand is a “parameter” controlled by the “grasping” (pre-shaping) mechanism controlling the hand posture and not by the “transport” mechanism controlling visually guided reaching. It is worth noting that the same experiment has been planned with young infants and the corresponding results are reported as part of

Workpackage 4. The experimental setup of the posting experiment is shown in Figure 4. In this particular experiment we integrated the control of the orientation with the transport phase of the reaching task modeling the incremental acquisition of motor skills found in human infants.



A



B

Figure 4: A: Setup of the "posting" experiment. B: Images acquired by the visual system of the robot to control the orientation of the paddle-hand.

In the experiment performed so far no force/torque information is used to correct the orientation error.

Learning to push

With the idea of starting to address the problem of the learning of the consequences of self-generated actions (and keeping in mind that we did not have a hand to control), we decided to study the action of pushing. In particular we investigated how a robot can learn which motor synergy is more appropriate to push an object in specific directions.

Learning to act involves not only learning the visual consequences of performing a motor action, but also the other way around, i.e. using the learned association to determine which motor action will bring about a desired visual condition. Along this line we have shown how our humanoid robot uses its arm to try some simple pushing actions on an object, while using vision and proprioception to learn the effects of its actions. We have shown how the robot learns a mapping between the initial position of its arm and the direction the object moves in when pushed, and then how this learned mapping is used to successfully position the arm to push/pull the target object in a desired direction. In Figure 5 an example of a learned action is shown. After the robot has identified the object and the target because of the different colors, it selects the proper learned action to push the object in the direction of the target.

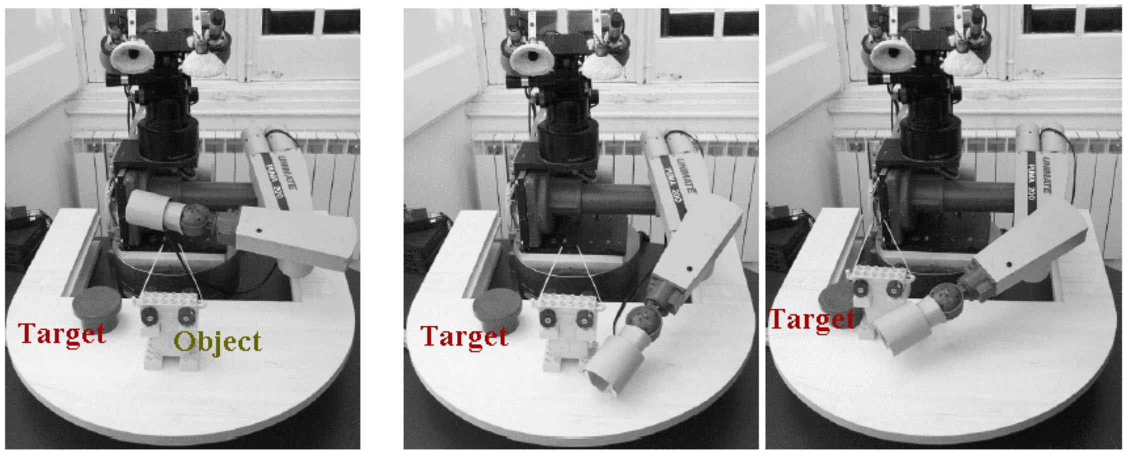


Figure 5.: Sample action after learning. The robot task is to push the "Object" towards the "Target". This is performed by a learned "swiping" motion.

2.3. Workpackage 3 - Biological Setups development and test

This Workpackage is devoted to the definition, realization and test of the experimental setups to be used to investigate the biological bases of the project. For the purpose of the project it will be necessary to acquire information about the trajectory and posture of a human arm as well a synchronized sequence of images of the arm performing the action. This information will be used to test the correlation between motor and visual data in the discrimination of different grasping actions. Therefore it is important that both the visual as well as the kinematic data is, as much as possible, analogue/similar to what perceived by the person executing the grasping.

2.3.1. Deliverables 3.1 and 3.2 – Biological data acquisition setup

This deliverable describes the experimental setup being developed for the acquisition of visual and motor data during grasping actions performed by humans. The motivation for building this setup is to start experimenting with algorithms, based on the processing of visual and motor data that could be used to extract, code, and recognize grasping actions. Visual data is acquired through two video cameras in a binocular stereo arrangement positioned so that the acquired video stream is very close to the “subjective” view of a person during manipulative actions. The motor data is acquired by means of a data-glove measuring the evolution in time of the posture of the hand (22 sensors on palm and fingers), position and orientation of the wrist (6 more sensors). Visual and motor data is acquired synchronously and stored on disk for off-like processing. Figure 6 shows the architecture of the acquisition setup composed of:

- Two *Watec WAT202D* digital cameras with PAL standard (768x576 pixels, 25 Hz of frame rate, color) acquired by two *Picolo Industrial* frame grabbers.
- A *CyberGlove* data-glove produced by *Immersion*, which consist of a glove mounting 22 sensors reading the hand joints angle.
- A *Flock of Birds* tracker produced by *Ascension*, it determines the position of a sensor in space.
- Two pressure sensors, to read the pressure applied by the thumb and the index onto object during grasping.

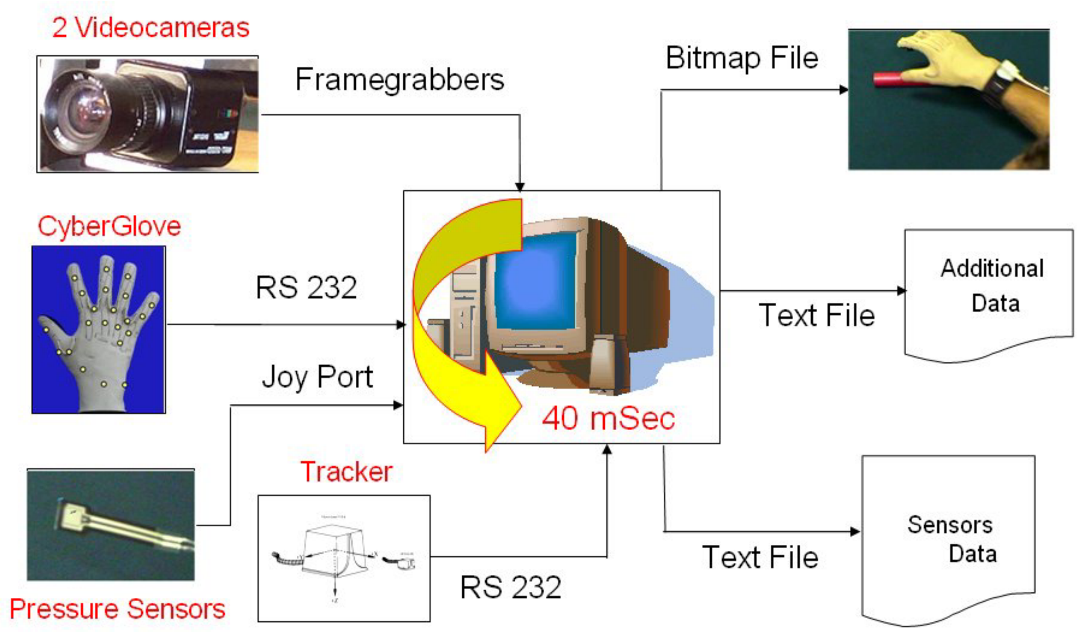


Figure 6: Configuration of the setup.

In the following, Figure 7 shows a sample sequence of monocular images. During the actual recording, stereo images are acquired and stored to disk. Figure 8 shows a sample recording from one of the joints of the Flock of Birds tracker.

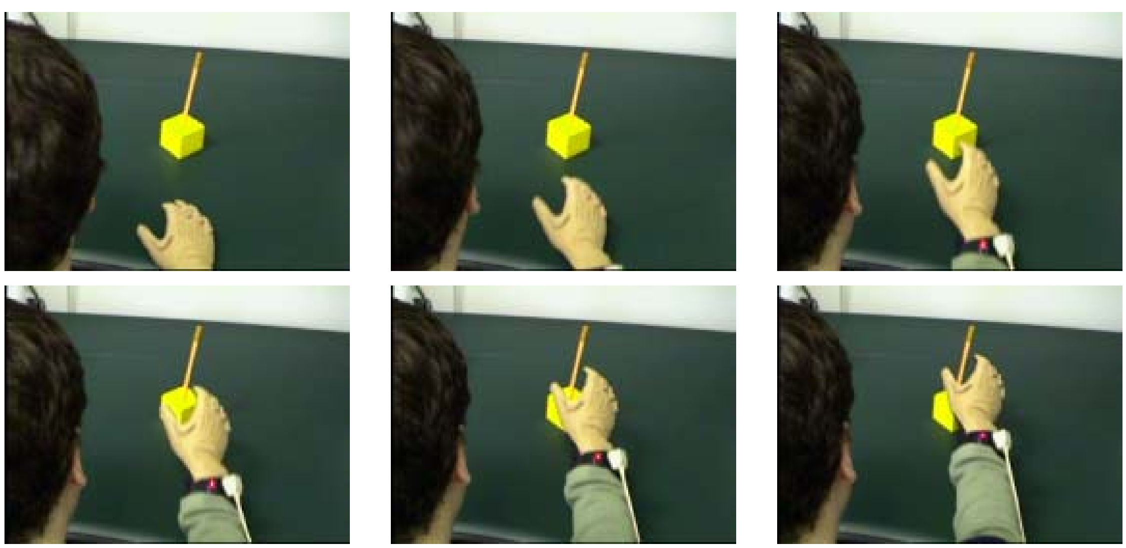
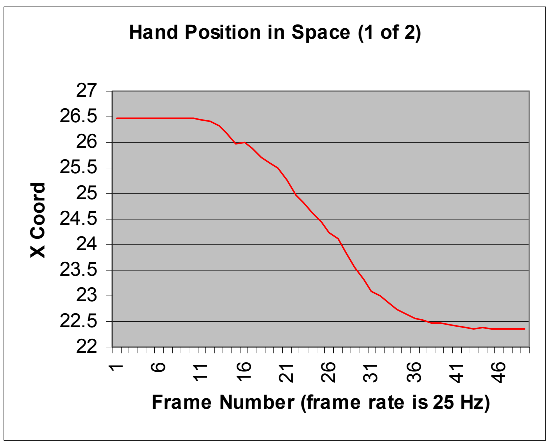


Figure 7: sample sequence from the right camera of a grasping action.



Hand-X	Hand-Y	Hand-Z
26.477859	12.379772	-21.0065
26.477859	12.362194	-21.01529
26.473464	12.370983	-21.019684
26.469069	12.366588	-21.019684
26.482253	12.353404	-21.01529
26.464675	12.379772	-21.024079
…………		
…………		

Figure 8: Numerical (right) and plotted (left) data from the positional sensor at the wrist.

2.3.2. Deliverable 3.3 - Data collection analysis and processing software

The software for data collection is composed of a calibration module, an acquisition module, and an off-line processing part. The **calibration module** is required to measure the position of the cameras with respect to the manipulation environment as well as the angles returned by the data-glove. Camera calibration is obtained by acquiring a set of images of a reference pattern while the calibration of the hand's joints is performed by means of reference hand postures. The **acquisition module** is started manually by the operator once all acquisition parameters have been defined (e.g. size of the stored images). During recording the images are stored as uncompressed files (to allow later off-line processing at the best possible image quality) while all other data is stored as text files to ease the following off-line read-out. The **data processing** module consists of a *Matlab* application. The tool opens the text file and reads the tracker, data-glove, and pressure values into memory. The data is then available to the user for further analysis e.g. image processing. Figure 9 illustrates the appearance of the application windows during the analysis.

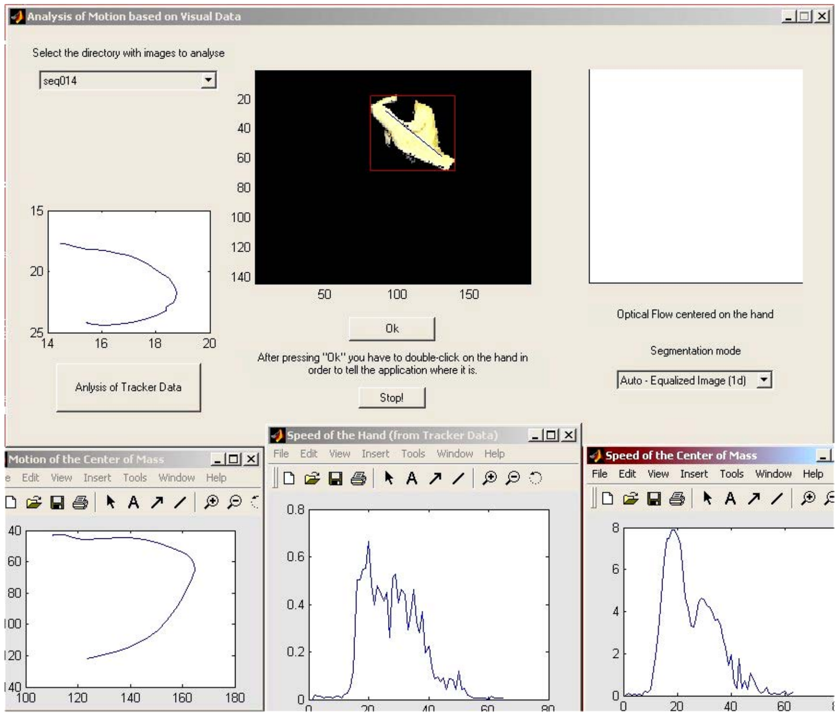


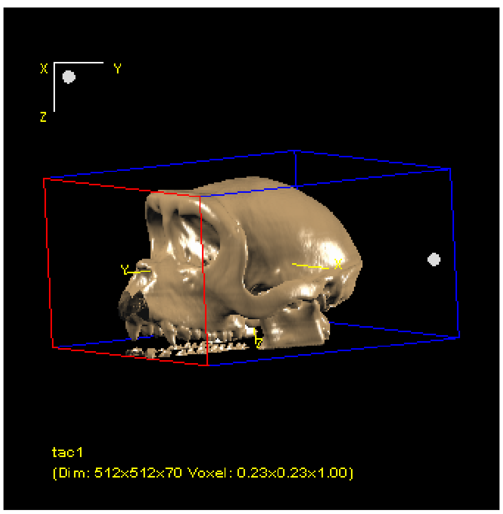
Figure 9: MATLAB windows during processing. The upper window shows traces obtained from the image sequences. The three lower windows show results of elaboration of the data-glove data.

Workpackage 4 – Experiments

Besides the robotic experiments described in section 2.2.3, additional experimental setups and related pilot/preliminary experiments were realized with monkeys and young children.

2.3.3. Deliverable 4.1 – Protocol for Monkey Experiments

This deliverable item describes the experimental procedure and the experimental protocols that will be adopted during the recordings in behaving monkeys. In particular the deliverable describes: 1) a new method – that is under development – to precisely design the 3D shape of the chamber to be fixed to the skull. This method is based on precise 3D measures of the skull reconstructed from CAT scan and the computer aided design of a chamber perfectly adhering to the surface of the skull over the recoding site. 2) The surgical procedure that will be followed to implant the chamber. 3) The details of the single unit recording procedure during the experimental sessions. Considering that the experiments will be performed with behaving monkeys the comfort of the animal and the accuracy of microelectrode stereotaxic positioning have been carefully optimized. 4) Finally the outline of the experimental protocol is described. The goal of the experiment is to test the properties of single mirror neurons. This requires first characterizing isolated neurons according to their preferred modality (sensory or motor) and specific "mirror" properties. Successive to the initial characterization the neuron will be recorded during meaningful (for the neuron) grasping actions. This response elicited by the same grasping action will be recorded in different conditions of "visual feedback" and for different classes of neurons. The activity will be analyzed by comparing the frequency of discharge in the different situations. Video recording of the grasping movements will be performed simultaneously to compute hand grip and trajectory using a method under development that renders unnecessary the application of passive or active infrared markers on fingertips. In Figure 10 a 3D representation of the skull of one of the monkeys is shown. These images, obtained through a CAT scan, are used to design the optimal shape of the chamber used to guide the microelectrode during in-vivo recording.



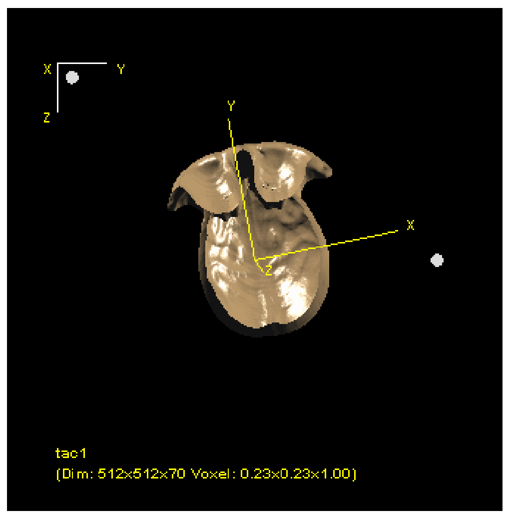


Figure 10 Left: Anterolateral view of the 3D reconstructed skull of monkey MK1, Right: Internal surface of the reconstructed skull.

2.3.4. Deliverable 4.2 – Protocol for the behavior development experiment

This Deliverable describes the experimental procedure and the experimental protocols that will be adopted during the behavioral experiments aimed at investigating the developmental timeframe of the mirror system. In particular during the initial months of the project two kinds of experiments aimed at studying the early development of mastering the adjustments of hand orientation in manual tasks have been designed: "the rotating rod experiment" and "the rod-hole experiment". In both cases the aim of the experiment is to investigate the onset and development of the goal-driven ability to control hand orientation. This ability is supposed to be a first step toward the ability to pre-shape the hand during the transport phase of grasping. Figure 11 shows the experimental setup developed.

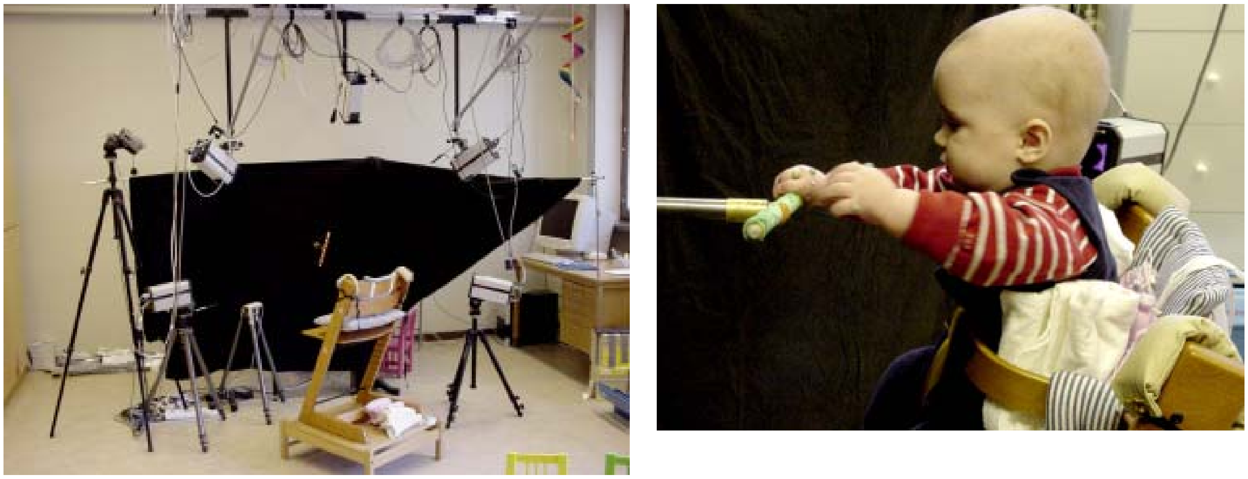


Figure 11: Experimental Setup with recording equipments and (right) close-up of infant performing the reaching/grasping action

2.3.5. Deliverable 4.3 - Preliminary results of the monkey experiments

This Deliverable describes some preliminary results of the monkey's single F5 neurons recording experiments. The experiment we are currently performing aims to investigate the role of visual feedback originating from hand self-observation during grasping execution, in modulating F5 premotor neurons discharge.

The experimental paradigm consists in the electrophysiological recording of single grasping neurons located in premotor area F5 in the monkey, during partial visual information of the monkey's grasping hand. In order to reach the experimental setup different steps have been done.

- CT based localization of the target region on the monkey skull and titanium chamber modeling.
- Chamber milling by using a computer controlled 3D plotter.
- Surgical implant of hydroxyapatite coated titanium parts.

Training

After surgery and recovery, monkey has been trained to:

1. Interact with experimenters and laboratory environment.
2. Perform the grasping task.

To this purpose a specially designed apparatus has been prepared in our lab. It consists of a box located in front of the monkey (see the *grasping in light.mpg* videoclip included in the CD attached to this document), in which little pieces of food are hidden. In order to reach for the food, the box could be opened by the monkey by means of a precision grip performed on a small plastic cube working as handle to open the door (see Figure 12).

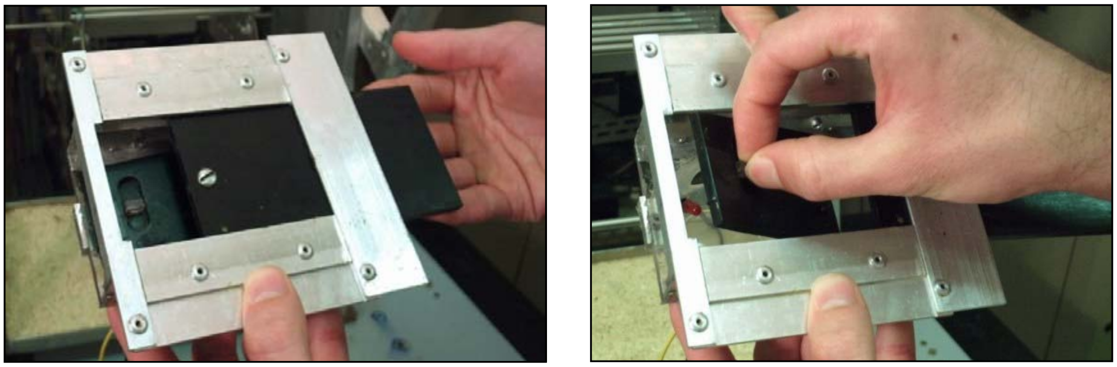


Figure 12: Apparatus designed for the monkey experiment. Left: the sliding outer door opened by the experimenter before each movement. Right: The handle used by the monkey to open the food box.

Note that an additional, outer door, sliding laterally, covers the to-be-grasped handle before the beginning of each trial.

The starting signal is given to the monkey by the opening the outer door. In this way the translucent handle becomes visible and the animal grasps it to open the door and get the food. The handle is dimly back-illuminated by a red LED, allowing the monkey to correctly perform the grasp also in a complete dark condition.

Two trigger stimuli are generated by the apparatus and sent to a computer for spikes alignment. The first one signals the moment at which the monkey is touching the handle. The second one is generated by a pyroelectric infrared sensor (adjustable in position) that can be used to signal precise spatial locations of the moving hand before the contact with the handle. Both triggers can be used to generate a very brief (few microseconds) flash by using a xenon lamp connected to the computer controlling the task's temporal sequences.

Experimental paradigm and neuron recordings

During experimental sessions, the behaving monkey seats on a restraining chair with the head fixated by means of a specially designed frame in which four rods are pulled onto the four titanium spheres chronically implanted on the skull. Arms and legs are allowed to freely move. A specially designed prototype of micromanipulator is firstly used to calibrate the electrode tip position and then to move it to the desired location. The electrode is then inserted through the dura mater with an angle of 40° (with respect to the sagittal plane) in the premotor cortex by using a hydraulic micropositioner. Spikes are amplified, filtered and fed to an A/D converter for storage on a computer. The acquisition program has been specifically realized by our team. The electrical activity is acoustically amplified by an Audio Monitor and it gives to the experimenter a fundamental feedback during neuronal testing. F5 area has been already electrophysiologically delimited by establishing the borders with neighboring areas (FEF, rostrally and F4, caudally) by single neuron studies and intracortical microstimulation.

In order to test the experimental hypothesis (*motor invariants firstly validate the visual information related to one own acting hand, then the system becomes capable to extract motor invariants also during observation of actions made by others*), F5 premotor neuron activity is investigated in different experimental conditions (see *mpeg* video clips included in the CD attached to this document):

a) Grasping in full vision (*grasping in light.mpg*).

b) Grasping in dark with no hand visual feedback (*grasping in dark.mpg* Note the the hand is visible in the video, but not to the monkey, because of an infrared illuminator).

c) Grasping in dark with instantaneous visual feedback before contact (*flash on max ap.mpg*).

d) Grasping in dark with instantaneous visual feedback at object contact (*flash on touch.mpg*).

During grasping hand/wrist kinematics are recorded by means of a 3D video acquisition system developed in our laboratory. The system uses a catadioptric camera to capture at high frequency (60 Hz) stereo images of monkey's hand movements (see figure above). Specifically designed 3D reconstruction algorithms are used to reconstruct frame by frame the 3D position of critical points (fingertips, wrist) extracted from stereo-images. This recording system gives us the advantage to measure kinematic parameters without placing markers on monkey's hand.

2.3.6. Deliverable 4.4 - Preliminary results of the behavior experiment

The results presented in this Deliverable refer to the “Rotating rod” experiment. The dynamic properties that have to be anticipated when reaching for an object are not just those related to object position, but also changes in the orientation and form of the object. In the present experiment infants’ pre-adjustments of reaching movements to a rotating object was studied. Few main questions were asked. First, will young infants adjust the orientation of the hand to a rotating rod when reaching for it? Second, are these adjustments geared to object velocity? Third, will the adjustments anticipate object rotation? And, finally, will the adjustments only affect the grasping phase of the reach like in adults or will the approach be affected as well? Kuypers (1973) and Lawrence and Kuypers (1968a, b) showed that the neural pathways controlling the proximal and distal muscle groups have different organizations in the adult monkey. This differentiation becomes quite apparent with maturation. If the rotational adjustments of the hand are independent of the approach adjustments in adult subjects, then the emerging independence of these mechanisms will reflect the maturation of the manual motor system.

Experimental procedure. The apparatus is shown in Figure 11. At the start of the experiment, the infants were placed in an infant chair in front of the rod at a distance that was out of reach. At the different trials, the rod was either stationary or rotated in the frontal plane. When it was stationary, its orientation was either horizontal or vertical. Two velocities were used: 18°/s and 36°/s. The direction of motion was either clockwise or anti-clockwise. Thus, there were 6 conditions in the experiment. Each of them was presented twice making altogether 12 trials. The order between trials was randomized.

Results and Discussion. In several ways, the results indicate that approaching and grasping an object are independent actions. First, the analysis of movement units showed that the rotation of the rod affected the rotational adjustments of the hand but not the approach of the rod. The maximum approach velocity was not dependent on the rotational velocity of the rod but the maximum rotational velocity of the hand was. Finally, the small correlations between the rotational velocity and approach velocity support the conclusion that these two actions are relatively independent. These results support the earlier results by Jeannerod and associates (Stelmach, Castello & Jeannerod, 1993; Paulignan, Jeannerod, MacKenzie, & Marteniuk, 1991).

The rotation of the rod was found to affect the grasping action but not the approach action. When the rod rotated faster, the hand rotated faster as well. In other words, the subjects’ attempts to grasp the object appropriately took the rotation of the object into account. The results also indicate that the grasping of the object is geared to its rotation in such a way that the hand moves with the object.

The results show that the grasping of the rod is prospectively controlled irrespectively of the rotational speed of the rod. The average angular difference between the hand and the rod was found to be the same in spite of the rotational velocity of the rod. In fact, the angular difference was the same when the rod was stationary as when it moved with 36°/s. A major effect of age was found, however. As an example of the results obtained Figure 13 shows how the average angular difference between the hand and the rotating rod at contact, decreased with age from 30° at 6 months of age to 15° in adults. Age effects in manipulative skills between 6-month-olds and adults are expected thus it is more remarkable when they do not show up. Two of the measures of the rotational movements of the hand did not show any age effects. They were the size of movement units and the maximum velocity of the reach.

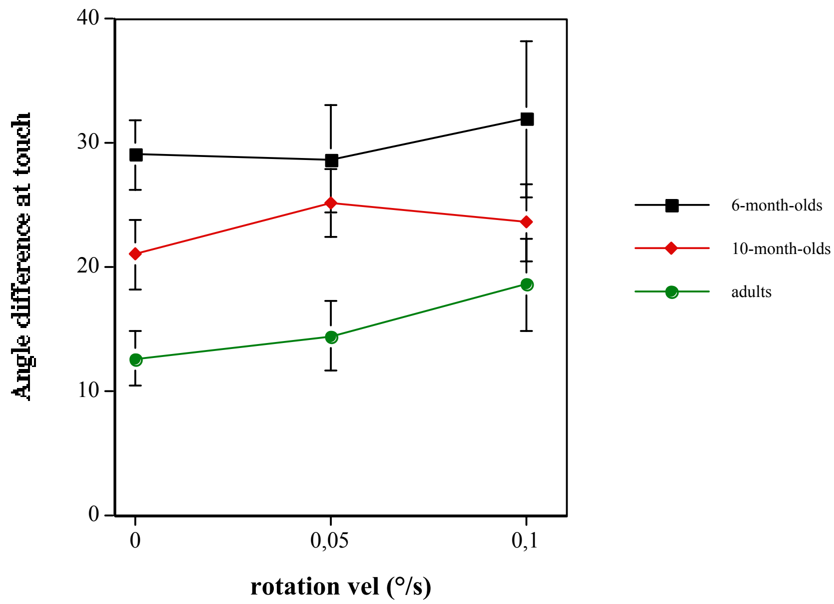


Figure 13: Angular difference between hand and rod at encounter.

3. Deviations from planned activities

As we already anticipated in the intermediate progress report due at month 6, still in the framework of the scientific problem of action recognition on which the MIRROR project is based upon, we decided to investigate some aspects in humans with electrophysiological techniques. By using transcranial magnetic stimulation (TMS) we made some preliminary observations showing that a motor resonance, similar to that observed in monkey mirror neurons, can be evoked not only by action viewing but also when a subject is passively listening verbal stimuli acoustically presented (Fadiga et al, Eur J Neurosci, 2002;15, 399-402). It is obvious that, in this case, the “mirror” effect involves at the cortical level not hand but tongue motor representation. TMS reveals such a speech listening- induced motor facilitation by showing a specific increase of motor potentials recorded from tongue muscles. We are therefore now investigating whether this motor resonance induced by speech listening represents a mere epiphenomenon or whether it reflects an involvement of motor centers in speech perception (as suggested by the famous Liberman’s theory of speech perception). To this purpose we are using repetitive TMS to test whether the magnetic stimulation of speech-related premotor centers is able to interfere with subjects’ performance during phonologically and/or semantically related perceptual tasks.

4. Plans for next period

The overall goal of the next period will be to propose and test a model of the ontogenesis of the "mirror system". Our ideas in this respect are outlined in the ANNEX 1 which constitutes the "optional" document to be sent before the review.

With specific reference to the scientific workpackages of the project, the planned activity is briefly described.

4.1. WP2 – Robot

In the second year we will start using the robot hand and address the control of grasping. What we intend to do is to see how it is possible to learn the association between object's shape and location and the shape of the hand. Initially, also from the results obtained during the first year, we will study how to associate the orientation of the hand with the orientation of a rotating rod and how this skill interacts with the approach phase of grasping. During the learning phase the robot will also use the visual, proprioceptive and motor information generated during the motion of its own hand to try to correlate the "look" of the grasping action with its "feel and move". The model used for this aspect of the research (which is the basis of the mirror system) will be suggested by the experiments performed with human adults (WP 3) as well as monkeys and infants (WP 4). Also in this workpackage we intend to investigate the minimum set of visual primitives required to identify which pre-shaping action is best suited to grasp objects with different shapes. For this purpose we will use, initially, a minimum set of three objects consisting of a sphere, a cylinder (power grasp) and a small object (precision grip) to stimulate/test three different grasping actions.

4.2. WP3 – Biological Setup and Test

In this workpackage we intend to record and analyze a set of grasping actions performed by human adults. During the last meeting in Ferrara it was decided to start acquiring a database of actions composed of three grasp types, each one recorded 5 times for 10 subjects (150 recordings). This data will serve to implement and test learning algorithms. Initially we will look for correlations between kinesthetic and visual data to find the simplest method to combine this data that allows distinguishing the different grasps. Later on we will test the discrimination power on the basis of visual information alone in the "self" as well as the "mirror" view. What we mean by "simplest" here is any visual information that does not explicitly require the computation of hand posture from stereoscopic vision (a very imprecise measure) but it is based on more "global" (and therefore more robust) computations (e.g. global motion information). The results of this analysis will be tested in the robotic model developed in WP2.

4.3. WP4 – Experiments

In relation to the "**behavioral development**" experiments with human infants, we will continue to investigate the appearance of manipulation (grasping) skills in tasks similar, but more complex than the "rotating rod" experiment performed this year and described in sections 2.3.4 and 2.3.6. In particular: we intend to do two kinds of investigations:

1. Studies on how infants learn to fit objects into holes: how the objects should be oriented in order to pass through the hole. Object of various difficulties are going to be used. In addition to basic tests of how task complexity and age are related, learning experiments are planned in which an adult model will show the infants how to go about fitting the object into the hole.
2. Experiments on how infants go about catching objects moving with high velocities along complicated trajectories. We will also test how infants can handle gaps in the flow of information when reaching for objects by having the objects pass behind occluders before they come within reaching distance.

As to the **monkey experiments** the second year of the project will be devoted to acquire data, to validate data from the first monkey on other animals and, possibly, to explore manipulative neurons in the parietal cortex. The protocol of the experiment will be similar to the one described in section 2.3.5. We will try to investigate the role of visual feedback in the ontogenesis of the mirror system.

Also the results obtained in these experiments will be transferred to the robot setup where it will further be used to validate the implementation.

In addition, as anticipated in the "Deviation from planned activities" Section of the Periodic Progress Report N°1, UNIFE will continue the investigation on the possible relationships between motor resonance and speech perception with transcranial magnetic stimulation.

5. Effort in person months in the period 1.9.2001 – 31.10.2002

			DIST				UNIFE				IST				UU				TOTAL			
			Period		Cumulative		Period		Cumulative		Period		Cumulative		Period		Cumulative		Period		Cumulative	
WP/Task		Deliv.	Est	Act	Est.	Act	Est	Act	Est.	Act	Est	Act	Est.	Act	Est	Act	Est.	Act	Est	Act	Est.	Act
WP1																						
D1.1	Project Presentation	1	0.5	0.5				0.2				0.2				0.2			0.5	1.1		
D1.2	Dissemination and Use Plan	6	1				0.3				0.3				0.3				1.9			
D1.3	Management Report 1	6	0.5	0.5															0.5	0.5		
D1.4	Periodic Progress Report 1	12	0.5	0.5			0.2	0.2			0.2	0.4			0.2	0.2			1.1	1.3		
D1.5	Management Report 2	12	0.5	0.5				0.2				0.2				0.2			0.5	1.1		
D1.6	Management Report 3	18																				
D1.7	Periodic Progress Report 2	24																				
D1.8	Management Report 4	24																				
D1.9	Technology Implementation Plan	30																				
D1.10	Final Report	30																				
	WP-Total		3	2			0.5	0.6			0.5	0.8			0.5	0.6			4.5	4		
WP2																						
D2.1	Robot setup specifications and design	6	2	2			2	2			4	1.5			1	1			9	6.5		
D2.2	Robot setup	8	8	8							2	2							10	10		

D2.3	Visual primitives for object identification	8	2	2							8	6							10	8		
D2.4	Basic robot behaviors	12	3	3							4	2							7	5		
D2.5	Architecture of the learning artifact	18		4								1								5		
D2.6	Robot testing and technology assessment	24																				
D2.7	Final demonstration and results	30																				
	WP-Total		15	19			2	2			18	13			1	1			36	35		
WP3																						
D3.1	Biological data acquisition setup specifications	6	2	2			2	2			1	1.5			2	2			7	7.5		
D3.2	Biological data acquisition setup	8	2	2			5	5			4	0.5			4	4			15	12		
D3.3	Data collection analysis and processing software	12	5	5			1	1				0.5							6	6.5		
D3.4	Modeling of the mirror neurons representation	18																				
	WP-Total		9	9			8	8			5	2.5			6	6			28	26		
WP4																						
D4.1	Protocol for the monkey experiments	6	1	1			4	4											5	5		
D4.2	Protocol for the behavior development experiments	6													4	4			4	4		
D4.3	Preliminary results of the monkey experiments	12					10	10											10	10		
D4.4	Preliminary results of the behavior development experiments	12													10	10			10	10		

D4.5	Final results of the biological experiments	24																				
D4.6	Comparison between “artificial” and “real” neurons	30																				
	WP-Total		1	1			14	14							14	14			29	29		
	TOTAL		28	31			25	25			24	16			22	22			98	93		

6. Cost breakdown for the Reporting period

PART E-2 - INTEGRATED COST STATEMENT IN EURO TO BE SUBMITTED BY *COORDINAT0R*

For period from 1.9.2001 to 31.8.2002

Contractors	Costs											
	Costs	Personnel	Durable equipment	Subcontrac-ting	Travel and subsistence	Consumables	Computing	Protection of *knowledge*	Other specific costs	Administrative and financial coordination costs	Overheads	TOTAL
DIST – Univ. Genova	Est.	52,423		60,000	8,000	8,000				9,474	33,873	171,770
	Act.	45,722	3,277	54,151	10,331	10,326				2,968	33,874	160,649
Univ. Ferrara	Est.	23,700	12,500	4,000	5,000	25,000					13,240	83,440
	Act.	22,580	4,526	5,289	3,684	27,969			8,839		13,520	86,407
Univ. Uppsala	Est.	32,504	9,996		8,000	6,000					11,300	67,800
	Act.	43,430	101		5,603				716		9,970	59,821
IST – Lisbon	Est.	33,636		2,000	6,000	4,000					79,856	125,492
	Act.	43,254		2,400	4,327	152					74,648	124,781
TOTAL	Est.	142,263	22,496	66,000	27,000	43,000				9474	138,269	448.502
TOTAL	Act.	154,986	7,905	61,840	23,945	38,447			9,555	2,968	132,012	431,657

7. Index of the accompanying CD-Rom

Some of the results obtained and experimental recordings are better presented by means of videos. The CD-Rom attached to the present document contains contribution from all partners as detailed in the following paragraphs.

7.1. DIST -- University Of Genoa

Preliminary experiments in pre-grasp orientation

Here we study the pre-grasp orientation of the robot end-effector. The task in this case is the insertion of the end-effector into a slit; the robot learns how to pre-orient the wrist so that the action is successful. The "insertion task", considered here as a simplified type of grasping, which is used to study how to learn the preparation of a motor action. One video.

Learning to act on objects

In this experiment we show how a humanoid robot uses its arm to try some simple pushing actions on an object, while using vision and proprioception to learn the effects of its actions (first video). Afterwards this knowledge is used to position the arm to push/pull the target in a desired direction (second and third video).

Mirror neurons

We use a precursor of manipulation, i.e. simple poking and prodding, and show how it facilitates object segmentation, a long-standing problem in machine vision. The robot can familiarize itself with the objects in its environment by acting upon them. It can then recognize other actors (such as humans) in the environment through their effect on the objects it has learned about. Four videos.

Setup for the acquisition of visual and motor data from human subjects during grasping actions

The main goal here is to build a setup to acquire data from human subjects performing different types of grasps. We are able to record motor (position and orientation of the hand, position of the fingers) as well as visual data (sequence of stereo images). Two videos.

7.2. IST – Istituto Superior Tecnico in Lisbon

3D reconstruction and depth segmentation from log-polar images

The process takes a pair of log-polar images and computes a dense disparity map that allows for depth segmentation of the scene. It is based on a set of disparity channels whose responses are combined in a probabilistic framework to obtain the final depth map. One of the important aspects is that depth discontinuities are preserved, thus being useful for problems of figure-ground segmentation based on depth cues. See DI-2.3 for more details.

The first four videos illustrate depth maps obtained when looking at a person or at a hand. The segmentation results are also shown both for the hand and the upper body. The fifth (last) video illustrates the cortical (log-polar) images as they are represented and processed internally to the system. Five videos.

Gesture Imitation

These videos illustrate the approach developed for an artificial system to imitate the arm gestures performed by someone. When the demonstrator performs a gesture (first video), the system starts by segmenting the hand in the images based on skin color information. This information is used with the View Point transformation (see DI-2.3) to align the demonstrator's gestures to the point of view of the system. Finally, the Sensory Motor map is applied to generate the adequate arm configurations as shown in the second video. Two videos.

7.3. DP – University Of Uppsala

Rotating rod experiment

Infants' ability to adjust hand orientation when grasping a rotating rod has been studied. The rod to be reached for was either stationary or rotated. The results show that reaching movements are adjusted to the rotating rod in a prospective way and that the rotating rod affects the grasping but not the approach of the rod. One video.

7.4. DBS – University Of Ferrara

In-vivo recordings of mirror neurons in behaving monkeys

Different classes of neurons are recorded during grasping action in different conditions of "visual feedback". The videos show grasping actions performed in four different conditions: 1) with ambient illumination; 2) in the dark; 3) with a flash of light at the instant of maximum finger aperture; 4) with a flash of light at the instant of touch. Four videos.

8. Tentative Agenda of Review Meeting

Venue: Groot Begijnhof, Huis van Chièvres, Middenstraat 14,Leuven, Belgium

Date: Wednesday December 4,

Time: 13:30-15:30.

Attendees: DIST: Giulio Sandini, Giorgio Metta

Universty of Uppsala: Claes von Hofsten

University of Ferrara: Luciano Fadiga

IST-Lisbon: Josè Santos-Victor

TENTATIVE AGENDA

Introduction

13:30	Overview of Mirror Project and Results	Giulio Sandini

Highlights of first years results

13:40	The role of visual Feedback in the genesis of mirror neurons	Luciano Fadiga
13:55	Prospective hand adjustment in infant reaching	Claes von Hofsten
14:10	Learning simple manipulation in a robot	Giorgio Metta

Discussion

14:30	Questions/Answers
15:30	End of meeting