Grasping and Manipulation in Humanoid Robotics

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Abstract. Humanoid robotics is attracting the interest of many research groups world-wide. In particular, developing humanoids requires the implementation of manipulation capabilities, which is still a most complex problem in robotics. This paper presents an overview of current activities in the development of humanoid robots, with special focus on manipulation. Then we discuss our current approach to the design and development of anthropomorphic sensorized hand and of anthropomorphic control and sensory-motor coordination schemes. Current achievements in the development of a robotic human hand prosthesis are described, together with preliminary experimental results, as well as in the implementation of biologically-inspired schemes for control and sensory-motor co-ordination in manipulation, derived from models of well-identified human brain areas.

1 Introduction

Today Humanoid Robotics is the ‘Grand Challenge’ for robotics research. Such challenge stands as the natural evolution of advanced robotics but also represents the ancient dream of humans to replicate themselves. Thus, from one side humanoid robotics responds to the need for useful machines helping humans in a variety of activities, which has evolved from industrial to service robotics [1] and then to personal robotics [2]. On the other, it represents the 3rd Millennium attempt to imitate nature and to replicate humans, as the highest paradigms of virtuosity, which in the past has been pursued since ancient time by building “automata” [3]. Nowadays, the field of humanoid robotics, is attracting the interest of many research groups worldwide. Important efforts have been devoted to the objective of developing humanoids and impressive results have been achieved, from the technological point of view, especially for the problem of biped walking.

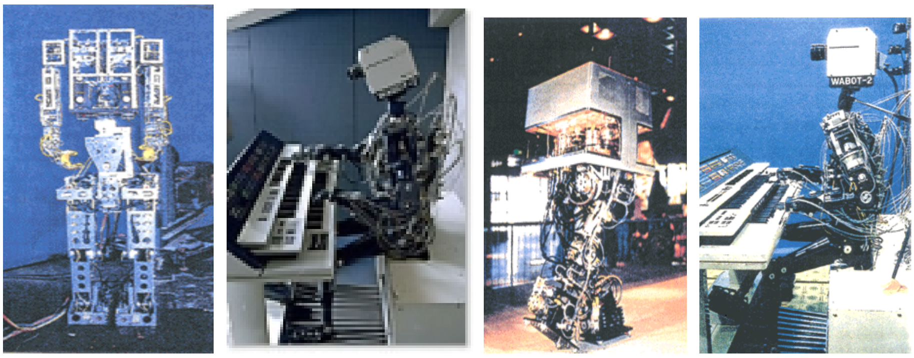
Manipulation is an essential capability of humanoid robots. Much work has been devoted to investigate manipulation in the last decades.

This paper comprises five sections. The first section describes the state of the art of humanoid robotics, of robotic hands and of prosthetic hands. The second section describes the proposed approach for manipulation in humanoid robotics. The third and fourth sections presents respectively our current approach to the design and development of anthropomorphic sensorized hand and to the realization of anthropomorphic control and sensory-motor coordination schemes for manipulation. Finally, in the fifth section, the conclusions are presented.

1.1 Humanoid Robotics

The first human-like modern robot built in the world was developed in 1973 by the bioengineering research group at the Science and Engineering Department of the Waseda University. It was named WABOT-1 (Waseda Robot No. 1) and it consisted of a limb control system, a vision system, and a conversation system [4]. Wabot-1 was able to communicate with a person in Japanese and to measure distances and directions to the objects using external receptors, artificial ears and eyes, and an artificial mouth. The Wabot-1 walked with his lower limbs and was able to grip and transport objects with his hands. A picture of Wabot-1 is shown in Fig.1 (a).

WABOT-2 (see Fig.1 (b)), the musician robot, has been also developed by Waseda University in 1984 as the natural evolution of WABOT-1[5]. WABOT-2 was able to play music with a concert organ and it was exhibited at the Science Exposition held in Tsukuba in 1995, where it played music within the Japanese Government Pavilion.



(a) (b) (c) (d)

Fig. 1. The Humanoid Robots (a) WABOT-1, (b) WABOT-2, (c) WHL and (d) WASUBOT developed at Waseda University.

In 1985, Hitachi Ltd, in collaboration with Waseda University, developed WHL-11 (Waseda Hitachi Leg 11) a robot able to walk statically on a flat surface at 13 seconds per step and to turn. A picture of WHL is shown in Fig.1 (c).

Waseda University has also developed in 1985 WASUBOT, another musician robot. WASUBOT performed a concerto with the NHK Symphony Orchestra, playing "Aria on the G-string" by J.S. Bach at the opening ceremony of the International Science and Technology Exposition held in 1985 (see Fig.1 (d)).

More recently, the problem of developing a humanoid robot has been investigated by many research groups throughout the world and especially in Japan.

In Japan new humanoid projects, started in the last decade, have been proposed by the Waseda University, Honda Motor Co, University of Tokyo and by ETL of Tsukuba.

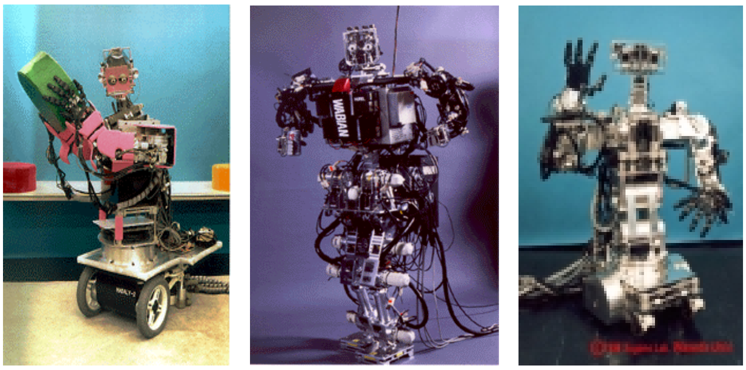
The Humanoid Project of Waseda University, started in 1992, is a joint project of industry, government and academia [6]. The project aims at developing robots which support humans in services, tertiary and industry and that share with humans information and behavioral space, so particular attention was given to the problem of human-robot interaction.

In 1995, the Humanoid Project of the Waseda University has produced its first prototype, the robot Hadaly–1 [7], whose name is derived from that of a female robot appearing in a novel written by Villiers de l'Isle Adam, a 19th century French novelist, titled "L'eve future". Hadaly 1 was able to implement several basic informational interactions with humans by combining audio-visual information, voice dialog and gesture motion using a four DOF manipulator arm.

In 1997, Waseda University integrated the technologies developed in the first phase of the project, fabricating two new humanoid robots named Hadaly 2 and Wabian (WAseda Bipedal humANoid) [6].

Hadaly 2, developed for improving the physical interaction ability of Hadaly 1, is intended to realize information interaction with humans by integrating environmental recognition with vision, conversation capability (voice recognition, voice synthesis), and gesture behaviors. It also possesses physical interaction function for direct contact with humans and behaviors that are gentle and safe for humans.

WABIAN is a robot with a complete human configuration that is capable of walking on two legs, and it is capable of carrying things. Furthermore, it has functions for information interactions, a specification intended for use at home.



(a) (b) (c)

Fig. 2. The Humanoid Robots (a) Hadaly-2, (b) Wabian, and (c) Wendy developed within the Humanoid Project of Waseda University.

The latest result obtained within the Humanoid Project of Waseda University is the robot Wendy (Waseda ENgineering Designed sYmbiont), which has been developed by improving each subsystem of Hadaly–2 in order to better exploit human-robot interaction. In particular, safety (impact and collision safety) and operability (mobility and dexterity) have been considered essential requirements for the design of human symbiotic robot. Dexterity and mobility of the robot have been evaluated by experimental tasks, such as picking up object on the floor and breaking eggs [8], [9]. See Fig.2 (c) for a picture of Wendy.

Impressive results have been obtained, from a technological point of view, by Honda Motor CO. Ltd. with their Humanoid Robots P2 and P3 [10]. The Honda Humanoid Project, started in 1986 aims at developing a robot able to coexist and collaborate with humans in the execution of tasks, doing what a person cannot do.

The first phase of the project, approximately one year, was spent on determining the aspect and the structure of the robot in order to realize a robot able to operate in a human environment. Since the robot was designed to be used in home, it should be able to move through rooms with furniture and going up and down stairs. So, in the design phase, particular attention was posed to the problem of the mobility of the robot and especially to the problem "foot/leg-walking mobile function", that was implemented mimicking the human walks with legs and feet.

The first prototype of the Honda Humanoid Robot, called P2, was disclosed in 1996 and its picture is shown in Fig.3 (a). P2 is a self-contained humanoid robot with two arms and two legs able to walk, to turn while walking, to climb up and down stairs, to push a cart and to tighten a nut. Afterwards, Honda presented P3 (see Fig.3 (b)), an evolution of P2, which was reduced in size and improved in walking capability and performance.

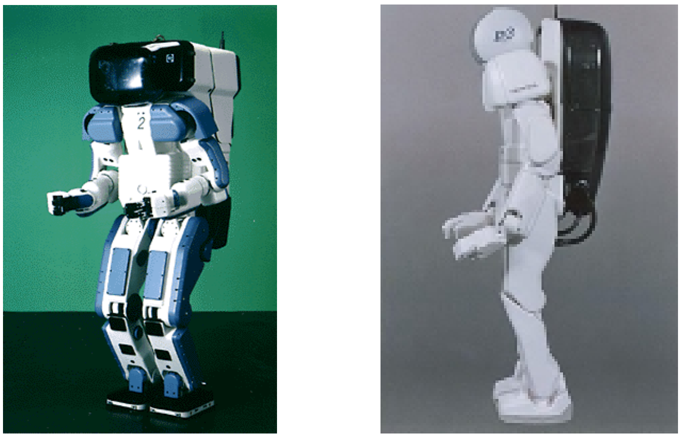

(a) (b)

Fig. 3. The Honda Humanoid Robots: (a) P2 and (b) P3.

Still in Japan, remarkable results have been also achieved by the Department of Mechano-Informatics of the University of Tokyo with the Saika project [11] (Fig.4 (a)), by the Humanoid Interaction Laboratory of the Electrotechnical Laboratory of Tsukuba with ETL-Humanoid robot “Jack” [12] and by Japan Science and Technology Corporation with the Humanoid Robot DB [13] (Fig.4(b)). Studies on human-robot interaction, on human-like movements and behavior and on brain mechanisms of human cognition and sensory-motor learning are carried on by these laboratories on their humanoid robots.

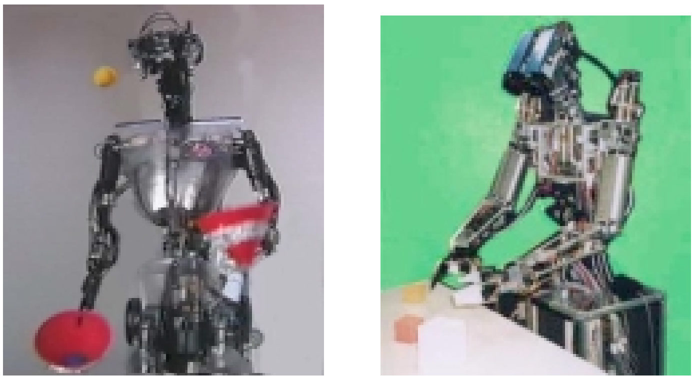
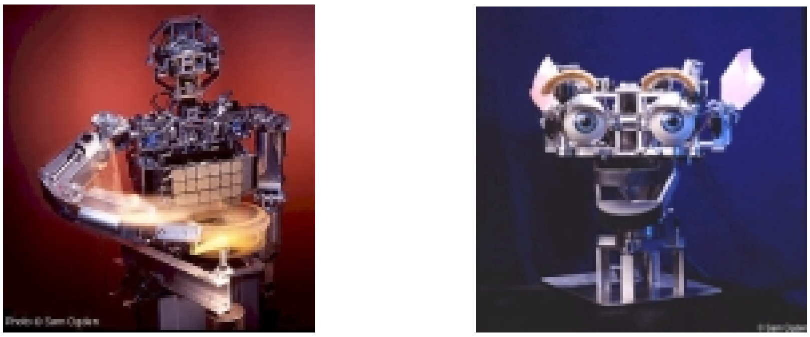

(a) (b)

Fig. 4. (a) the Saika and (b) the BD Robots.

In the USA, a great contribution to the design of a humanoid robot and in particular to the study of human-robot interaction and human cognition have been provided by the Artificial Intelligence Lab of the Massachusetts Institute of Technology within the COG Project [14]. The project, started in 1993, aims at developing a humanoid robot, named COG (from Cognition), in order to explore and understand human cognition. Perceptual systems and motor systems includes visual system, vestibular system, auditory system, tactile system, kinesthetic system, two six DOF arms, a torso with two DOF waist, a one DOF torso twist, a three DOF neck, and three DOF in the eyes (Fig.5 (a)).



(a) (b)

Fig. 5. (a) The COG Humanoid Robot and (b) Kismet.

Further visual-auditory platforms have been built by the same laboratory in order to deeply investigate relationships between vision and audition and social interaction between robots and humans. Kismet (see Fig.5 (b)) is a stereo active vision system augmented with facial expression analogous to happiness, sadness, surprise, boredom, anger, calm, displeasure, fear and interest.

In Europe, Humanoid Projects are currently carried on by the Chalmers University of Technology of the Goteborg University and by the University of Karlsruhe.

The goal of the project carried on by the Chalmers University of Technology is to produce a full-size, bipedal humanoid robot with human dimensions and weight. At present, the plan is to build the robot around a plastic human skeleton that will be controlled by a hierarchy of evolutionary systems. A prototype of the robot named ELVIS (see Fig.6 (a)) has been built. The objective of ELVIS is to try various hypotheses regarding hardware and control software. The motivation of the work relies on a strong belief in the future importance of humanoid robotics for industry, research and society in general. The final goal of the project is to create an autonomous humanoid able to walk and that can communicate verbally with humans.

ARMAR (Fig.6 (b)), developed by the Karlsruhe University, is an autonomous mobile humanoid robot for supporting people in their daily life as personal or assistance robot. Currently, two anthropomorphic arms have been built up and mounted on a mobile base and studies on manipulation based on human arm movements are carried on [15] [16].

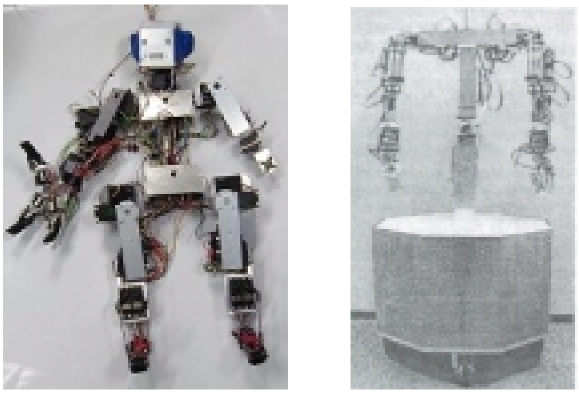

(a) (b)

Fig. 6. (a) the ELVIS Robot by the Chalmers University of Technology and (b) ARMAR by the *Karlsruhe University.*

1.2 Robotic Hands

Developing humanoids poses fascinating problems in the realization of manipulation capability, which is still an unsolved problem in robotics. For its scientific content and for its usefulness in most robotics applications, the problem of manipulation has been deeply investigated and many results are already available, both as hands and sensors and as control schemes.

Impressive dexterous hands have been built in the past [3]. The popularity of designing and building robot hands is demonstrated by the large number of universities and research organizations that have hands named after them. In the past, dexterous hands have been developed to perform laboratory research on grasping and finger manipulation. With this objective J. Salisbury designed the Stanford/JPL hand [17]. The hand has three fingers, each of them has three DOF and four control cables; the hand is controlled by an actuator pack of 12 DC servo motors with 25:1 speed reducers. The majority of Salisbury control work is in the area of fingertip prehension; the object is already grasped in the fingertips with the finger imparting motion to it (see Fig.7 (a)).

The same field was investigated with the Utah/MIT hand that closely copies the outward appearance of the human hand (see Fig.7 (b)) [18]. The Utah/MIT Dexterous Hand has four degrees-of-freedom in each of three fingers, and a four DOF thumb. The geometry of the hand is roughly anthropomorphic. The thumb is, however, permanently in opposition and the phalanx lengths and joint positions have been altered to facilitate the routing of tendons. The 16 DOF hand is actuated using an antagonistic tendon approach, which requires a system of 32 independent polymeric tendons and pneumatic actuators. The pneumatic actuators are fast, low friction, and can generate relatively high forces. The lowest level of control for the Utah/MIT Dexterous Hand includes an analog controller for each of the 16 DOF which executes position control and tendon management. Higher levels of control are mapped onto a distributed VME-based architecture, consisting of 68000 family processors running under VxWorks from a Sun workstation host.

An alternative approach was represented by the Hitachi Ltd [19]. Hand with its radically different shape memory alloy (SMA) actuation technology. The hand was characterized by a high power-to-weight ratio and a high compactness. The Hitachi Hand used a large number of thin SMA wires; each finger had 0.02 mm diameter SMA wires that were set around the tube housing of the spring actuators. The SMA wire, when heated by passing electric current through it, reacted by contracting against the force of the spring (see Fig.7 (c)).

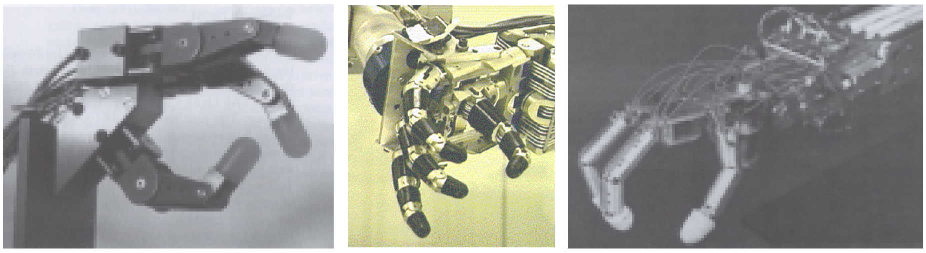
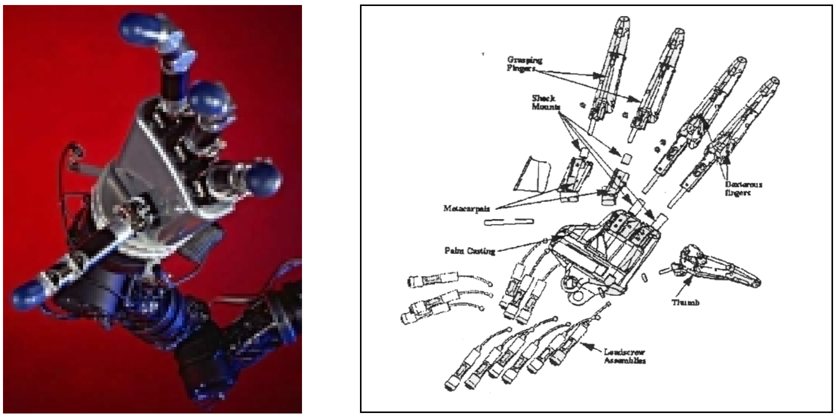

(a) (b) (c)

Fig. 7. (a) the Stanford/JPL hand, (b) the Utah/MIT hand and (c) the Hitachi Ltd. hand.

More recently, the DLR (Deutches zentrum fur Luft-und Raumfahrt) developed a multisensory four-finger hand with in total twelve degrees of freedom with the declared goal to integrate all the actuators in the hand palm or directly in the fingers [20]. Force transmission in the fingers is realized by special tendon, which are optimal in terms of low weight and backlash despite of fairly linear behavior. Each finger shows up a 2 DOF base joint realized by artificial muscles and a third actuator of this type integrated into the bottom finger link. The aim of this project is to develop a robotic hand for space operations e.g., handling drawers, doors, and bayonet closures in an internal lab environment (see Fig.8 (a)).



(a) (b)

Fig. 8. (a) The hand developed by DLR and (b) the Robonaut Hand by the NASA Johnson Space Centre.

The development of a robotic hand for space operations is currently ongoing also in the Robotic Systems Technology Branch at the NASA Johnson Space Centre [21]. The goal of the Robonaut project is to reduce the extra-vehicular activity (EVA) burden on space station crew and also to serve in a rapid response capacity. The Robonaut Hand has a total of fourteen degrees of freedom. It consists of a forearm which houses the motors and drive electronics, a two-degree-of-freedom wrist, and a five finger, twelve degree of freedom hand. The forearm, which measures four inches in diameter at its base and is approximately eight inches long, houses all fourteen motors, twelve separate circuit boards, and all the wiring for the hand. The hand itself is broken down into two sections: a dexterous work set which is used for manipulation and a grasping set which allows the hand to maintain stable grasp while manipulating or actuating a given object (see Fig.8 (b)).

1.3 Prosthetic Hands

In parallel to this, the problem of developing prosthetic hands has been widely addressed in the field of rehabilitation technologies: the main goal is to manufacture human-like hands, whose main requirements are cosmetics, noiselessness and low weight and size. At present, there are almost five different ways to restore the functionality of an amputated patient [22]. Among them, a still valid option is the use of a *cosmetic prostheses*, generally made by duplication of the contralateral arm (see Fig.9 (a)). These prostheses are often lighter than others and require less maintenance, but they have poor or no functionality. Conventional *body-powered prostheses* are powered and controlled by gross body movement, usually of the shoulder.

Myoelectrically controlled prostheses are at present the best way to partially restore the functionality of an amputated limb, but until now they are just one-degree-of-freedom grippers controlled by one or two channels of electromyographic signals (EMG), either in proportional or switching mode. The most advanced myoelectric hand commercially available is probably the OttoBock SUVA Hand (see Fig.9 (b)).


(a) (b)

Fig. 9. (a) A cosmetic prosthesis and (b) the OttoBock SUVA Hand.

Finally, *hybrid prostheses* combine a body-powered with a myoelectric prosthesis in case of shoulder disarticulation level amputations.

Another approach, consisting in designing prostheses specifically designed for some activities, i.e. for fishing or bowling has been adopted by several industries (see Fig.10 (a) and (b)).

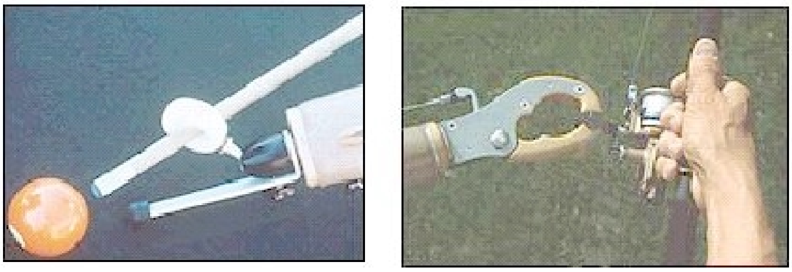

(a) (b)

Fig. 10. (a) Pool and (b) fishing prostheses.

Despite of improvements in the design and realization of new components and materials in the last period, so far most prostheses remains simple grippers with only one or two degrees of freedom. This situation was due to the belief that more than two active degrees of freedom could not be easily controlled by the muscles on the residual limb of a human. Moreover, there is the strict requirement of embedding all the components within a housing closely replicating the shape, size and appearance of the human hand. Only recently, several groups have designed prosthetic hands with four or more d.o.f. [23] [24], by combining the input of one or two bipolary EMG channels with information available from sensors on the prosthesis in order to allow the electronics to control multiple d.o.f. In Fig.11 the Losh hand (a) and the NTU Hand (b) are shown.


(a) (b)

Fig. 11. (a) The Losh hand and (b) the NTU Hand.

Starting from the assumption that recent progresses in the design and realization of robotic hands have permitted to increase grasping functionality and dexterity without solving the main limitations of robotic hands (size and weight) and taken into account the recent parallel development in the field of human prostheses, then it can be argued that an integrated approach can lead to the development of anthropomorphic hands for humanoids. More in general, the proposed approach to the design and development of humanoid robots relies on the integration of humanoid components, intended both as anthropomorphic hardware systems, and as software modules implementing anthropomorphic control and behavioral schemes.

2 The proposed approach for manipulation in humanoid robotics

The proposed approach to humanoid robotics is based on the consideration that biomedical robotics can provide significant contributions to the investigation of the problems related to the development of humanoid components and anthropomorphic control and behavioral schemes.

Biomedical robotics, as well as the wider field of biomedical engineering, has a two-fold objective:

- to provide techniques and tools for medical applications;
- to provide techniques and tools for improving the understanding of biological systems.

Biomedical robotics includes the development of robots for surgery and for rehabilitation, and also the development of artificial organs and limbs.

Furthermore, biomedical robotics provides experimental platforms to validate models of biological systems, including human brain. Thus, it includes anthropomorphic robotics, intended as the development of components replicating human features, both in terms of sensors and actuators and in terms of control and behavior planning schemes.

Based on these considerations, investigating humanoids should take into particular account the advances and achievements of biomedical robotics.

Focusing the problem of manipulation in humanoid robotics, a general scheme is depicted in Fig.12. The scheme comprises of *Anthropomorphic Perception*, detecting external stimuli from the environment through anthropomorphic sensors and their early processing modules, *Anthropomorphic Processing*, elaborating the sensory information through techniques replicating human reasoning and behavior planning, and *Anthropomorphic Actions*, introducing motor actions in the environment through anthropomorphic actuators and control.

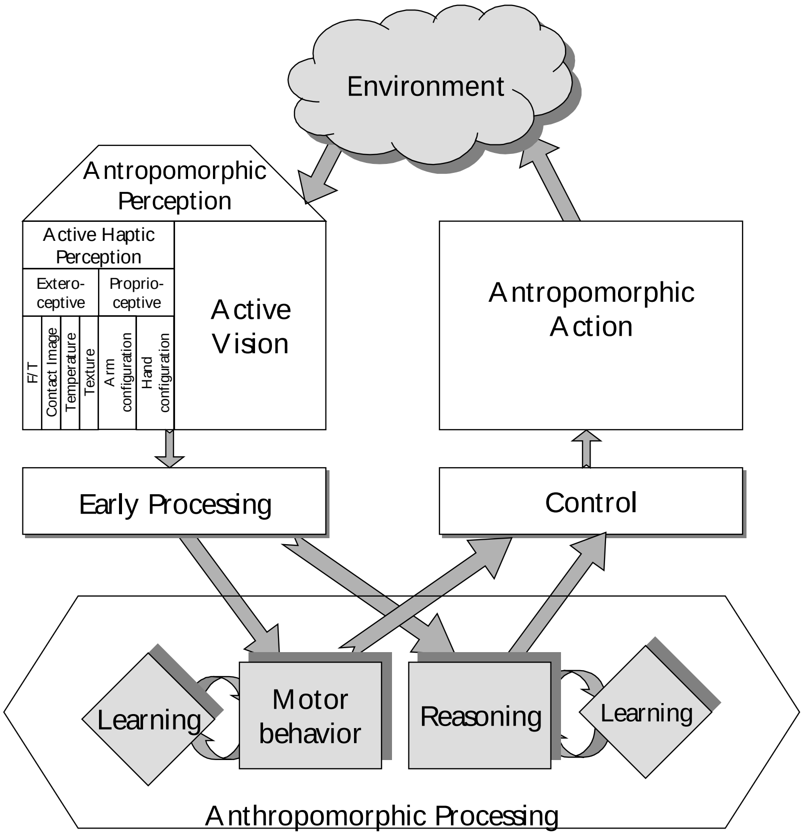


Fig. 12. The proposed scheme for manipulation.

The identified perception modalities are active vision and active haptic perception [25] [26]. By haptic perception we intend the integration of proprioception (e.g. perception of arm and hand current configurations) and exteroception (e.g. detection of applied force and torque, contact image, thermal properties and smoothness).

The proposed anthropomorphic processing is composed of two distinct levels: the low level of *motor behavior* and the high level of *reasoning* [27], both developed and refined through learning. By motor behavior, we intend the instinctive processes, while by reasoning we intend high level conscious cognitive processes. This duality is derived from the hypothesis that in human brains the higher levels can function independently from the motor system, as experimentally demonstrated by Roger W. Sperry [28].

The actuation system taken into consideration for humanoid manipulation comprises of anthropomorphic arm, hand and head.

The approach adopted by the authors for developing a humanoid manipulation system includes the development of anthropomorphic sensors and actuators starting from the results of the prosthetic field and the development of software modules starting from the results of anthropomorphic robotics in neuro-physiological studies. The following sections describe current achievements and work in progress in the two sectors.

3 Developing a biomechatronic hand

The main goal in designing a novel prosthetic/robotic hand is to pursue an integrated design approach in order to fulfil critical requirements such as cosmetics, controllability, low weight, low energy consumption and noiselessness. This approach can be synthesized by the term ‘biomechatronic design’, aimed at embedding different functions (mechanisms, actuation, sensors and control) within a housing closely replicating the shape, size and appearance of the human hand.

The first step towards this objective is to enhance the hand dexterity by increasing the DOF of the system. As mentioned by several authors [29] [30] the main problem is the limited space available to integrate actuators within the prosthetic hand. Recent progress in sensors, actuators and embedded control technologies are encouraging the development of a new generation of artificial hands, as demonstrated by the growing number of publications on this issue appeared in the last five years [21] [31] [32] [33] [34]. In our laboratories we have designed a biomechatronic artificial hand with the aim of achieving high dexterity and functionality.

3.1 Actuators architecture

The biomechatronic hand will be equipped with two actuating systems to provide a tripod grasping: two identical finger actuator systems and one thumb actuator system.

The finger actuator system is based on two micro actuators which drive respectively the metacarpo-phalangeal joint (MP) and the proximal inter-phalangeal joint (PIP); for cosmetic reasons, both actuators are fully integrated in the hand structure: the first in the palm and the second within the proximal phalanx. The distal inter-phalangeal joint (DIP) joint is driven by a four bar link connected to the PIP joint.

The grasping task is divided in two subsequent phases in which the two different actuator systems are active:

1) reaching and shape adapting phase;
2) grasping phase with thumb opposition.

In fact, in phase one the first actuator system allows the finger to adapt to the morphological characteristics of the grasped object by means of a low output torque motor. In phase two, the thumb actuator system provides a power opposition useful to manage critical grips, especially in case of heavy or slippery objects.

It is important to point out that the most critical problem of the proposed configuration is related to the high load resistance required to the microactuators during the grasping phase.

3.2 Kinematic architecture

A first analysis based on the kinematic characteristics of the human hand, during grasping tasks, led us to approach the mechanical design with a multi-DOF prosthesis structure (see Fig. 13).

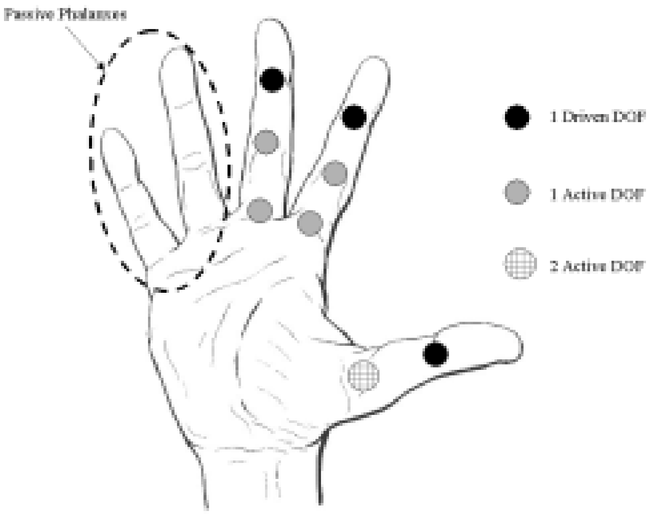


Fig. 13. Kinematic architecture of the biomechatronic hand

Index and middle finger are equipped with two active DOF respectively in the MP and in the PIP joints, while the PIP joint is actuated by one driven passive DOF.

The thumb movements are accomplished with two active DOF in the MP joint and one driven passive DOF in the IP joint. This configuration will permit to oppose the thumb to each finger.

The novel design technique can be represented as a loop, as shown in Fig.14.

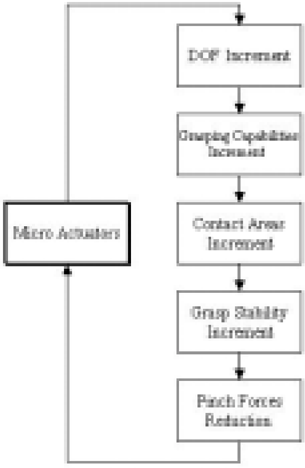


Fig. 14. Novel design approach loop

In particular, to demonstrate the feasibility of this approach we developed a two DOF prosthetic finger actuated by two micro drivers (based on DC brushless motor) 5 mm diameter. Due to the consequent enhanced mobility, the novel finger is able to provide an increased contact area between the phalanxes and the object during a grasping task. According to the proposed approach, we can accept a reduction in power actuation with the benefit of increasing contact areas and finally of enhancing grip stability.

3.3 Implementation of a first prototype of the finger

The two DOF finger is designed by reproducing the size and kinematics of a human finger as closely as possible. It consists of the three phalanxes and of the palm housing, that is the part of the palm needed to house the proximal actuator. Fig.15 shows a drawing and a photograph of the finger.

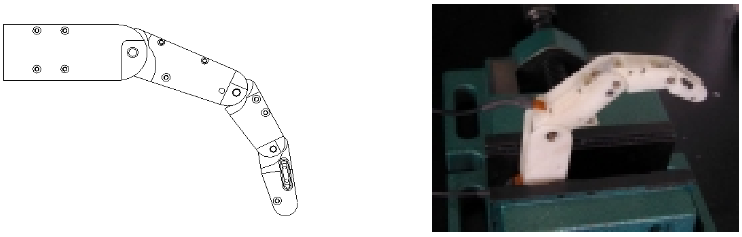


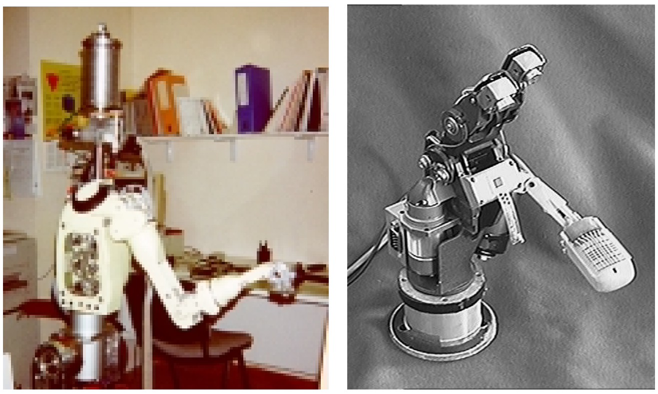
Fig. 15. General drawing and the first prototype of the finger

In order to match the size of a human finger, two micro motors are mounted respectively inside the palm and the proximal phalanx. This high integration level is achieved by enclosing the motors in a shell housing, where they are constrained only by the friction forces. This shell housing is obtained directly from the structure of the proximal phalanx. The output force is sufficient to move the phalanxes for achieving adaptive grip. Finally, the shell housing provides mechanical resistance of the shaft to both axial and radial loads. This turns out to be essential during grasping tasks, where loads, derived from the thumb opposition, involve the actuator system as well as the whole finger structure. The micro motors were used as linear actuators to directly drive MP joint and the PIP joint, while the driving force is transmitted to the DIP joint by a linkage. A complete hand is being developed and will be ready soon for tests [35].

4 Anthropomorphic sensory-motor co-ordination schemes

Based on the general framework of artificial perception and sensory-motor co-ordination in robotic manipulation proposed in Section 2, a number of sub-problems have been identified and solutions have been implemented and validated through experimental trials. A series of experiments has been carried out using an anthropomorphic robotic set-up, both in the sensory system and in the processing modules. In particular, the problem of grasping has been subdivided into: (a) planning of the pre-grasping hand shaping, (b) learning of motor co-ordination strategies, (c) tactile-motor co-ordination in grasping and (d) object classification based on the visuo-tactile information perceived by exploration.

The experimental set-up includes anthropomorphic sensors, such as a robotic fingertip integrating tactile, thermal and dynamic sensors, and a retina-like visual sensor, and anthropomorphic actuators, such as the 8 d.o.f. arm and a three-finger hand shown in Fig.16.



(a) *(b)*

Fig. 16. (a) The Dexter arm, showing an anthropomorphic mechanical structure and cable transmission, and (b) the Marcus hand equipped with the integrated fingertip; the Marcus hand was developed as a human prosthesis with three fingers and two and a half degrees of freedom (manufactured by S.M. Scienzia Machinale, Pisa (Italy)).

4.1 A neuro-fuzzy system for grasp planning

This first module has the aim to provide a robot with the capability of planning the proper hand configuration, in the case of a multi-fingered hand, based on the geometrical features of the object to be grasped.

In the attempt to replicate some human features, a fuzzy system has been implemented, so as to simulate the human ability of processing qualitative data. The set of rules of the fuzzy system has been built through a neural network, thus replicating the human capability of learning. A diagram of the neuro-fuzzy system is reported in Fig.17.

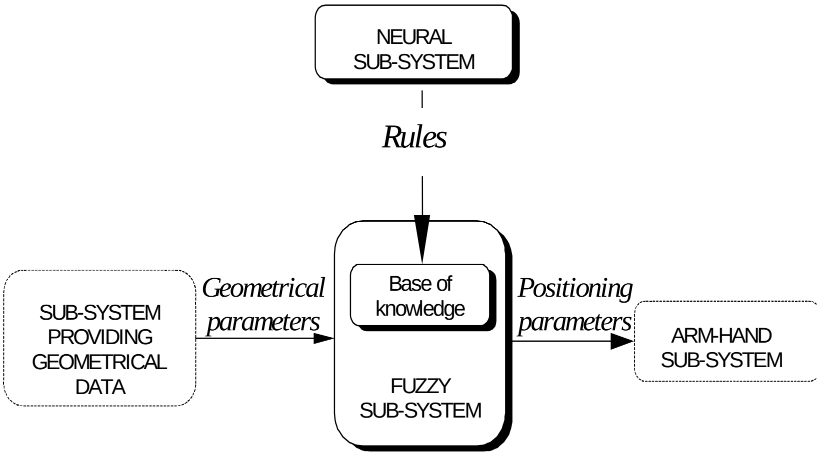


Fig. 17. Functional scheme of the neuro-fuzzy system for grasping planning.

‘Rough’ qualitative information on geometrical features of the selected object are supposed to be provided by a vision system. The fuzzy system, by applying a proper set of rules, determines the parameters for planning the hand configuration for grasping. More in detail, the base of knowledge on which the fuzzy system can process inputs and determine outputs has been built by a neural network that, after a supervised training on a reduced set of possible objects, generalizes the complete set of rules.

The trained system has been validated on a test set of 200 rules, of which 92.15% was correctly identified. A complete description of the work is given in [36].

4.2 Integration of vision and touch in edge following

In order to validate the anthropomorphic model of sensory-motor co-ordination in grasping, a module was implemented to perform a visual and tactile edge tracking, considered as the first step of sensory-motor co-ordination in grasping actions [37]. A diagram of the system is reported in Fig.18.

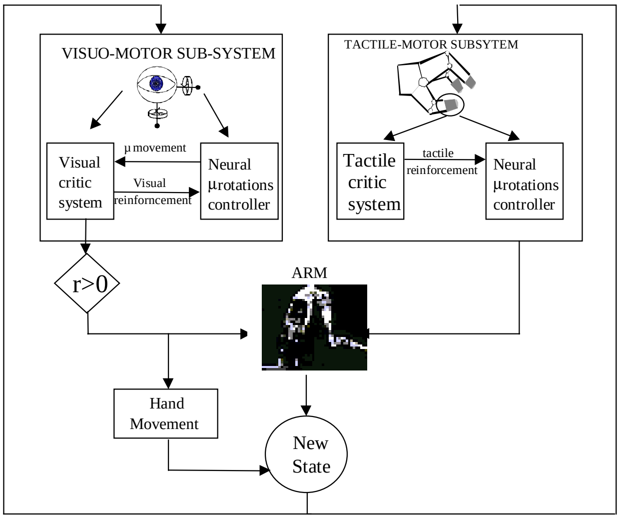


Fig. 18. Block diagram of the experiment on visual and tactile edge tracking

The proposed methodology includes the application of the reinforcement learning paradigm to back propagation neural networks, in order to replicate the human capability of creating associations between sensory data and motor schemes, based on the results of attempts to perform movements. The resulting robot behavior consists in co-ordinating the movement of the fingertip along an object edge, by integrating visual information on the edge, proprioceptive information on the arm configuration, and tactile information on the contact, and by processing this information in a neural framework based on the reinforcement learning paradigm. The aimed goal of edge tracking is pursued by a strategy starting essentially from a totally random policy and evolving via rewards and punishments. The neural approach has demonstrated the expected flexibility, adaptability and learning capability. The reinforcement learning paradigm has produced the expected natural-like behavior in robot movements. In few experimental trials, it was possible to observe the development of not optimal local policies (decreasing oscillations of the fingertip around the optimal fovealisation of the center of mass), due to the simple heuristic implemented in the experimental system for the calculation of the reinforcement.

4.3 Haptic-motor co-ordination in grasping

The problem of haptic-motor co-ordination in grasping has been studied by taking into account results from neuroscience and psychological studies and in particular the *Simian Elaboration Model* (SEM), proposed for haptic.motor co-ordination in Primates [38]. The first peculiarity of this biological model are that each sensory modality is perceived and transmitted in parallel fibers to the respective sensory areas where it is processed in parallel so as to maintain the topographic order of the sensed patterns. A second distinctive feature is the hierarchical arrangement of the modeled brain areas: this disposition allows a useful integration of higher areas devoted to complex tasks such as motor command generation.

Starting from the SEM, an artificial model has been developed and implemented through a neural-network-based computing architecture, which keeps the main peculiarity of the SEM. As shown in Fig.19, the use of neural networks allows parallel processing of sensory data and the different neural networks implementing different brain areas are hierarchically arranged.

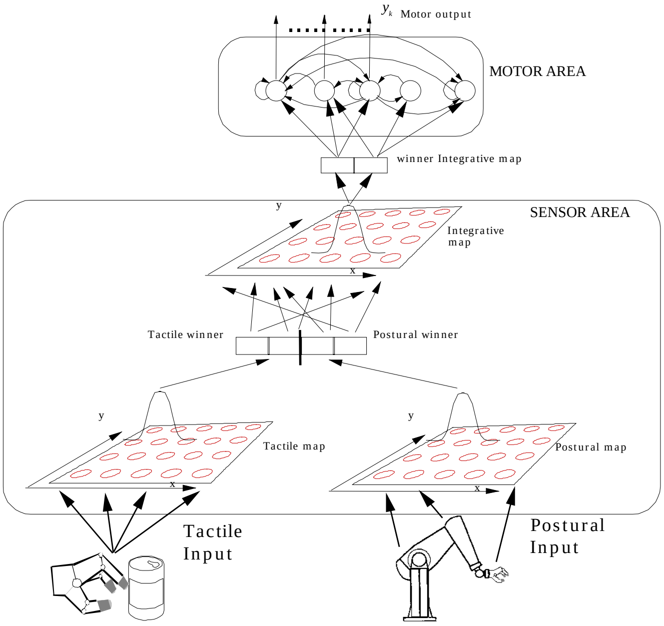


Fig. 19. A scheme of the proposed artificial neural system for haptic-motor co-ordination in grasping.

Motor control is actually directly involved in tactile perception, since touch is an intrinsically active sensorial modality for the need of bringing the receptors into contact with explored surfaces with proper positions and contact forces. These explorative motor actions can be performed only if a strict relationship between tactile and motor modalities has been previously established. In fact, the tactile perception for recognition or exploratory tasks requires an active strategy for acquisition of data. Moreover, sequences of contact positions are required for the acquisition of global object characteristics to build a map of it. For instance, the shape of an object does not constitute a local characteristic, in the sense that the Central Nervous System (CNS) could not understand the shape of the object from the sensorial information acquired by touching the object in just one position. It is necessary to touch the object in different positions to get a more general "picture" of the essential characteristics of the object being manipulated. The system that allows the combination of tactile and postural data takes the name of *haptic-system*. The problem is how to create a correct relationship between this haptic-system and the motor system in order to accomplish a specified manipulation task. One of the traditional psychological approaches to this learning processes is the Circular Reaction Scheme proposed by Piaget [39], for visual-motor co-ordination. A suitable adaptation of this scheme can properly "derive" a control scheme for haptic-motor co-ordination. This adaptation consists of a "translation" of the relevant parameters, such as visual target, spontaneous or endogenous movements and trajectory control, from the visual in the tactile context:

I. Tactile target. In the visual context, the target perceived in the outside world reference system is mapped by means of suitable transformation in the reference retinal system. Tactile receptors cannot "see" the target but the fingers can touch an object and the result of this action results in a tactile pattern activating the tactile reference system.

II. Endogenous movements. The implemented system is required to make some endogenous movements in order to hit the tactile target specified in full analogy to the visual context. Actually, the cerebral structures involved in making movements are the same both in tactile and visual context. The difference is in the range of the movements: in the visual context the movements are wider and coarser, in the tactile they are shorter and more refined.

III. Tactile trajectory. For the visual context, Bullock and Grossberg [40] showed how an accurate motor synergism, through control mechanism, can in a dynamic way and in real-time, rectify endogenous trajectory during the attempt to reach the object. The control mechanism is named *planned and automatic control*. The planned control oversees the "good" of the movements whilst the automatic control settles the variables of the mechanism necessary for the actual movements implementation, according to the system real condition. Both controls are implemented in the model and have the same control purpose of the trajectory that is seen as a temporal sequence of arm and hand postures. This posture is to lead to a "tactile trajectory" forming followed by a tactile pattern, starting from the initial point of contact up to tactile pattern target. The implemented system follows closely these assumptions and from an architectural point of view the neural approach relies on the integration of supervised and unsupervised neural networks with the reinforcement learning paradigm, aimed at replicating the human ability of auto-associating sensory and motor data and of learning such associations by attempts. The information process is the following:

- tactile and postural patterns are fed in parallel to two parallel neural networks (Tactile Map and Proprioceptive Map) ;
- each neural network of this level is implemented with a Self Organizing Feature Map (SOFM [41]), a well known algorithm capable of projecting over a two-dimensional area the sensed patterns preserving the topological relationship existing among them;
- the output of these sensory areas is projected to a higher SOM (called the Integrative Map) whose task is to integrate the different sensory modalities;
- the output of the Integrative Map constitutes of the input of a following neural network module implementing the Motor Area using a recurrent network modified according to a reinforcement learning rule.

The performance obtained, showed in Fig.20, confirms the validity of the proposed anthropomorphic artificial model. In fact, it was observed that, due to the learning capability of the system, the generated arm and hand movements closely reach the desired tactile target patterns with few iterations. A complete description of the work and of the experimental results are given in [42].

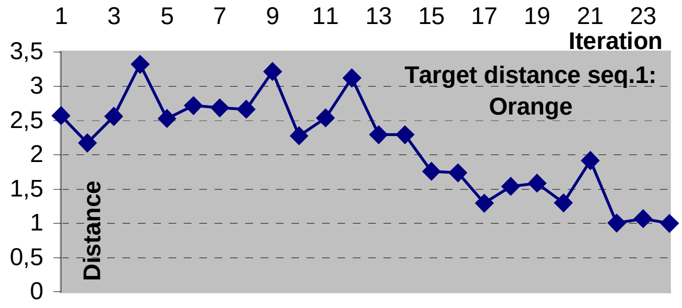


Fig. 20. A graphical representation of the error in reaching the target at each iteration.

4.4 Object recognition through visual and tactile exploration

Object classification by vision and touch has been obtained by replicating the human capability of integrating sensory data from different modalities into one perception at a low level, so as to achieve object recognition even without involvement of high level cognitive processes. The proposed neuro-fuzzy system is based on a multi-layer feed-forward neural network comprising two levels of features extraction and classification. The attention is focused on the choice of a neural network as a classifier system for the high parallel nature of the algorithm that has to process parallel signals. Furthermore, the complexity of the recognition task is significantly reduced via the iterative learning supervised process that, in the meanwhile, allows a robust and distributed knowledge representation and treatment.

The system comprises two levels of neural networks: the first is aimed at features extraction from the tactile (surface curvature) and dynamic signals (surface roughness); and the second, fed by the output of the previous ones, by the output of the visual recognition module and by the direct thermal sensor output, is aimed at recognition. The details of this experiment and of the results are given in [43].

4.5 Current work

Currently, ongoing work in the lab are directed at developing advanced neural schemes for object-oriented, adaptive reaching, grasping and manipulation in robotics. The goal is to transfer human planning processes to robotics, while incorporating experimental results from behavioral, anatomical, and neurophysiological studies. The technical objectives are the definition of an elementary hand gestures language by means of which to express any manipulative process, implementing it using biological neural networks that mimic the cooperation between cortical areas, basal ganglia and cerebellum during the manipulative behavior in order to build an adaptive neurocontroller capable of scaling up the generalizing capabilities to different robotic hands.

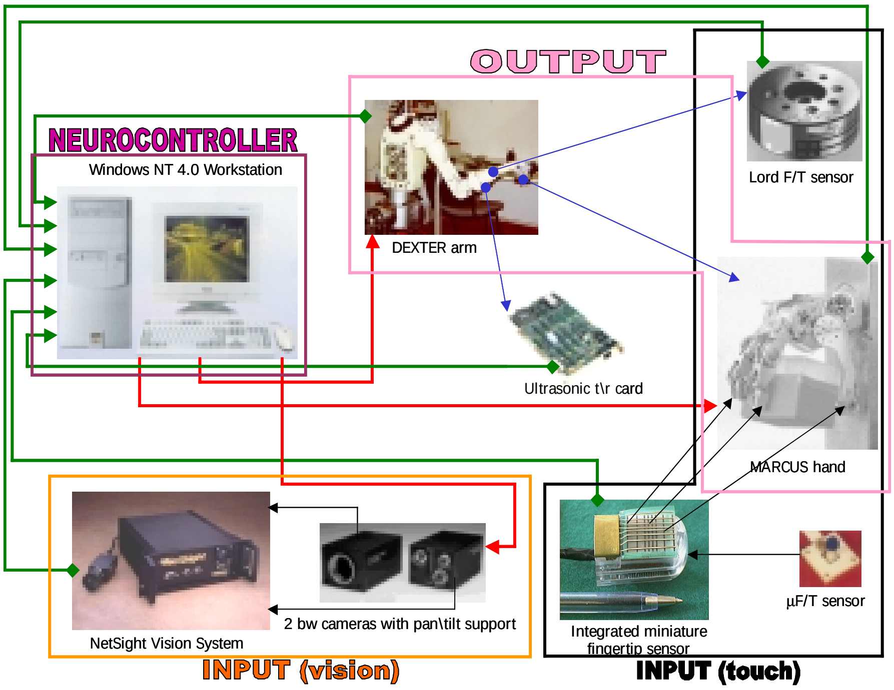


Fig. 21. The experimental platform.

A preliminary sketch of the experimental platform is illustrated in Fig. 21. It will allow the integration of different sensory modalities by means of a visual subsystems and a sophisticated tactile subsystem (including a robotic hand, a robotic arm, some miniature fingertip sensors extended with a F/T microsensor in the fingertip, and a wrist f/t sensor) and the control of the actuators by the innovative neurocontroller.

5 Conclusions

In this paper we presented an overview of humanoid robotics research, with emphasis on manipulation. We also discussed our approach to the development of a humanoid robotic system, based on the integration of humanoid components, to be developed by a biomechatronic design, which aims at embedding different functions (mechanisms, actuation, sensors and control) within a housing closely replicating the shape, size and appearance of the human limb. The control of such components and the behavior planning schemes for the humanoid robot are developed through anthropomorphic computing and learning paradigm, based on models of well-known brain areas. Focusing on grasping and manipulation, preliminary experimental results and current activities have been reported.

Future work aims at integrating the hardware and software modules into one robotic platform for human-like grasping and manipulation.

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