

# An Integrated Approach for the Design and Development of a Grasping and Manipulation System in Humanoid Robotics

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## Abstract

*The field of humanoids robotics is widely recognized as the current challenge for robotics research. Developing humanoids poses fascinating problems in the realization of manipulation capability, which is still one of most complex problem in robotics.*

*The paper, starting from an overview of current activities in the development of humanoid robots, with special focus on manipulation, presents the authors' approach to the design and development of anthropomorphic sensorized hands and of anthropomorphic control and sensory-motor coordination schemes. Current achievements at the Scuola Superiore Sant'Anna and Centro INAIL RTR (Research Centre on Rehabilitation Bioengineering) in the development of a robotic human 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, derived from models of well-identified human brain areas.*

## 1. Introduction

The field of humanoids robotics, widely recognized as the current challenge for robotics research, is attracting the interest of many research groups world-wide. Important efforts have been devoted to the objective of developing humanoids and impressive results have been produced, from the technological point of view, especially for the problem of biped walking.

In Japan, important humanoid projects, started in the last decade, have been carried on by the Waseda University and by Honda Motor Co.

The Humanoid Project of the Waseda University, started in 1992, is a joint project of industry, government and academia, aiming at developing robots which support humans in the field of health care and industry during their life and that share with human information and behavioral space, so that particular attention have been posed to the problem of human-robot interaction. Within the Humanoid Project, the Waseda University developed three humanoid robots, as research platforms, namely Hadaly 2, Wabian and Wendy [1][2].

Impressive results have been also obtained by Honda Motor Co. Ltd. with P2 and P3, self-contained humanoid robots with two arms and two legs, able to walk, to turn while walking, to climb up and down stairs [3].

Still in Japan, remarkable results have been also achieved by the Department of Mechano-Informatics of the University of Tokyo with the Saika project [4], by the Humanoid Interaction Laboratory of the Electrotechnical Laboratory of Tsukuba with ETL-Humanoid robot "Jack" [5] and by Japan Science and Technology Corporation with the Humanoid Robot DB [6]. 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.

In the USA, great contributions to the design of a humanoid robot and in particular to the study of human-robot interaction and human cognition have been given by the Artificial Intelligence Lab of the Massachusetts Institute of Technology within the COG Project, started in 1993 with the aim of developing a

humanoid robot named COG from Cognitive Robot [7].

Humanoid Projects are also currently carried on in Europe, by the Chalmers University of Technology of the Goteborg University with the Elvis Robot and by the University of Karlsruhe with the Armar Robot [8].

Developing humanoids poses fascinating problems in the realization of manipulation capability, which is still one of most complex problem in robotics. For its scientific content and for its utility 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.

The Stanford/JPL hand, designed by K. Salisbury, is a three-finger hand, with three DOF and four control cables for each finger. The majority of Salisbury control work is in the area of fingertip prehension: the fingers can impart motion to objects already grasped [9].

The same concept has led to the development of the Utah/MIT hand, closely copying the outward appearance of the human hand, with four degrees-of-freedom in each of three fingers, and a four DOF thumb [9]. The geometry of the hand is roughly anthropomorphic. 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.

An alternative approach in designing robotics hands has been proposed with the Hitachi Ltd. Hand with its radical shape memory alloy (SMA) metal actuation technology [9]. The hand is characterized by a high power-to-weight ratio and a high compactness. The Hitachi Hand uses a large number of thin SMA wires; each finger has 0.02 mm diameter SMA wires that are set around the tube housing of the spring actuators. The SMA wire, when heated by passing electric current through it, reacts by contracting against the force of the spring.

More recently, the DLR (Deutsches Zentrum für 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's palm or directly in the fingers [10]. Force transmission in the fingers is realized by special tendons. 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.

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 [11]. The Robonaut Hand has a total of fourteen degrees of freedom and consists of a forearm which houses the motors and drive electronics, a two-degree of freedom wrist, and a five fingers, twelve degree of freedom, hand. The hand itself is broken down into two sections: a dextrous 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.

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 [12]. Among them, a still valid option is the use of a cosmetic prosthesis, generally made by duplication of the contralateral arm. These prostheses are often lighter weight 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 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.

Despite of improvements in the design and realization of new components and materials of the last period, so far all the prostheses remains simple grippers with only one or two degrees of freedom. This situation was due to the conviction 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. [13] [14], by combining the input of one or two bipolar EMG channels with information available from sensors on the prosthesis in order to allow the electronics to control multiple d.o.f.

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 biomechatronic approach for the development of artificial hands

The main goal in designing a novel humanoid hands is to fulfil critical requirements such as functionality, controllability, low weight, low energy consumption and noiseless. These requirements can be fulfilled by an integrated design approach, called biomechatronic design, aimed at embedding different functions (mechanisms, actuation, sensors and control) within a housing closely replicating the shape, size and appearance of human hand.

The first step towards this objective is to enhance the hand dexterity by increasing the DOF and reducing size of the system. The main problem in developing such a hand, is the limited space available to integrate actuators within the hand. Anyway, recent progress in sensors, actuators and embedded control technologies are encouraging the development of such hand.

### 2.1. System Architecture

The proposed biomechatronic hand will be equipped with three actuators 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.

### 2.2 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 hand structure (Fig. 1). 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.

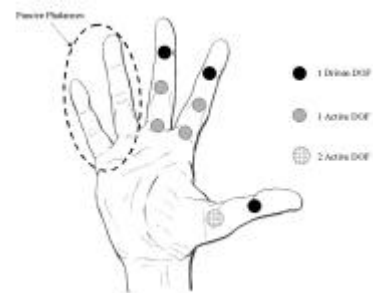


Fig. 1: The Kinematic architecture of the biomechatronic hand

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 see Fig. 2.

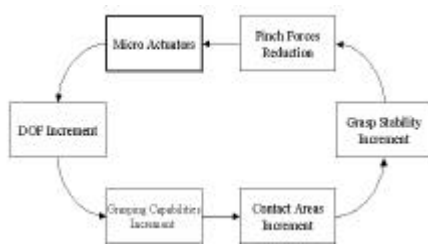


Fig. 2: Novel design approach loop

To demonstrate the feasibility of this approach, a two DOF prosthetic finger actuated by two micro drivers (based on DC brushless motor) 5 mm diameter has been developed. 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 proposed approach, we can accept a reduction in power actuation with the benefit of increasing contact areas and finally of enhancing grip stability.

### 2.1. Implementation of a first prototype of the finger

The two DOF finger is designed by reproducing, as closely as possible, the size and kinematics of a human finger. It consists of the three phalanxes and of the palm housing, that is the part of the palm needed to house the proximal actuator (see Fig. 3).



Fig. 3: 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 microactuators 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 using a linkage [15].

## 3. Anthropomorphic sensory-motor co-ordination schemes

A general framework for artificial perception and sensory-motor co-ordination in robotic grasping has been proposed at the ARTS Lab [16][17][18], based on the integration of visual and tactile perception, processed through anthropomorphic schemes for control, behavioral planning and learning. The problem of grasping has been sub-divided into four key problems, for which specific solutions have been implemented and validated through experimental trials, relying on anthropomorphic sensors and actuators, such as an integrated fingertip (including a tactile, a thermal and a dynamic sensor), a retina-like visual sensor, and the anthropomorphic Dexter arm and Marcus hand (see fig.4).

In particular, (1) planning of the pre-grasping hand shaping, (2) learning of motor co-ordination strategies, (3) tactile-motor co-ordination in grasping, and (4) object classification based on the visuo-tactile information are described and reported in the following paragraphs.

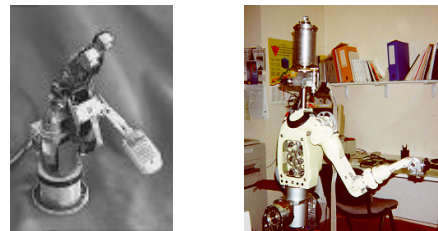


Fig.4: The Marcus Hand with the integrated fingertip and the Dexter Arm

### 3.1. A neuro-fuzzy approach to grasp planning

This first module has the aim of providing the capability of planning the proper hand configuration, in the case of a multi-fingered hand, based on geometrical features of the object to be grasped. A neuro-fuzzy approach is adopted for trying to replicate human capability of processing qualitative data and of learning.

A vision system provides 'rough' qualitative geometrical features of the selected object by applying a fuzzy logic paradigm, given as set of rules, the hand

configuration for grasping is planned. The base of knowledge on which the fuzzy system can process inputs and determine outputs is built by a neural network (NN), which, after a supervised training on a reduced set of possible objects, generalized a complete set of rules used to produce the parameters for arm/hand positioning, as output. The trained system has been validated on a test set of 200 rules, of which the 92.15% was correctly identified.

A complete description of the work is given in [17].

### 3.2. Integration of vision and touch in edge tracking

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

A diagram of the system is reported in fig. 5. The proposed methodology includes the application of the reinforcement learning paradigm to back propagation NNs, 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 from a totally random policy and evolving via rewards and punishments.

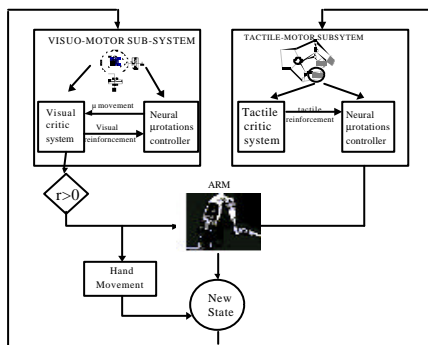


Fig. 5: Block diagram of the experiment on visual and tactile edge tracking

### 3.3. A neural approach to tactile motor co-ordination in grasping

A neural approach has been adopted for the development of sensory-motor schemes, based on the *Simian Elaboration Model* (SEM) of Primates [19]. The peculiarities of this biological model are that each sensory modality is perceived and transmitted by parallel fibers to the respective sensory areas, where it is processed in parallel so as to maintain the topographic order of the sensed patterns, and that the brain area is hierarchically arranged. These features are kept in the artificial system, relying on hierarchically arranged NNs (Fig.6).

The proper association between sensory data and motor schemes is achieved through an adaptation of the Piaget's Circular Reaction Scheme [20] and relevant parameters, (*visual target, spontaneous or endogenous movements and trajectory control*) to the tactile context.

The implemented system relies on the integration of supervised and unsupervised NNs with the reinforcement learning paradigm [21], aimed at replicating the human ability of auto-associating sensory and motor data and of learning such associations by attempts.

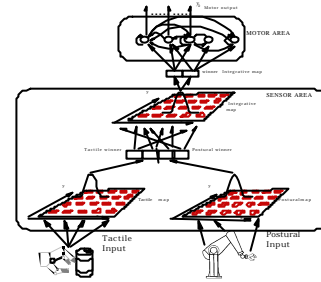


Fig. 6: The proposed artificial neural model for haptic-motor co-ordination.

The information process is the following:

- tactile and postural patterns are fed in parallel to two parallel NNs (Tactile Map and Proprioceptive Map) ;
- each NN of this level is implemented with a Self Organizing Feature Map (SOFM) [22], 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 NN module implementing the

Motor Area using a recurrent network modified according to a reinforcement learning rule.

Fig.7 shows the obtained performance, in terms of error in reaching the target.

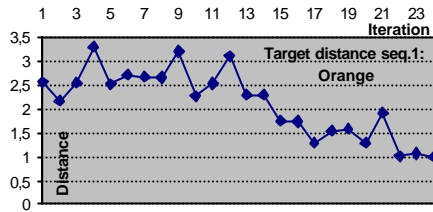


Fig. 7. Plot of the error in reaching the target.

Due to the learning capability of the system, the generated arm and hand movements closely reached the desired tactile target patterns with few iterations. A complete description of the experiments and of the results is given in [23].

### 3.4. Object classification by vision and touch

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 functional diagram of the system is reported in Fig. 8.

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 NN: 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 NNs, 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 its results can be found in [16].

### 3.5. 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.

A preliminary sketch of the experimental platform is illustrated in Fig.9. 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 microsensors in the fingertip, and a wrist f/t sensor) and the control of the actuators by the innovative neurocontroller (part of this current work is funded by the Syneragh Project - contract #BE-4505 of the EU).

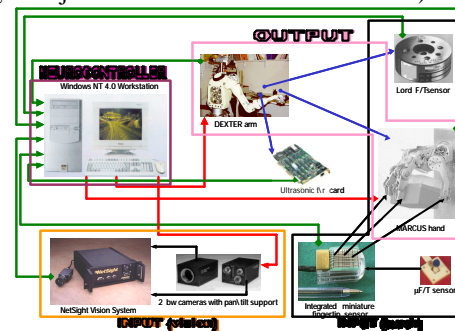


Fig. 9: The experimental platform.

## 4. Conclusions

An integrated approach to the development of an anthropomorphic manipulation system has been presented and discussed. An innovative biomechatronic approach for the development of an artificial hand has been presented, with preliminary experimental results, as well as a set of software modules for sensory-motor co-ordination in robotic grasping.

The authors' conclusions are that humanoid robotics can be approached by integrating human body components, such as human prostheses for upper limbs, and anthropomorphic control and behavioral schemes.

Future work on this track will lead, on one side, to the development of a three-finger biomechatronic artificial hand and, on the other side, to the development of the software modules replicating the human brain areas involved in sensory-motor co-ordination for manipulation.

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