

A Human-like Robotic Manipulation System Implementing Human Models of Sensory-Motor Coordination

P. Dario^{1,2}, C. Laschi², A. Menciassi¹, E. Guglielmelli², M. C. Carrozza²,
M. Zecca^{2,3}, L. Zollo², G. Teti², L. Beccai¹, F. Vecchi^{2,3}, S. Roccella^{2,3}

Scuola Superiore Sant'Anna

¹ CRIM (Center for Research In Microengineering)

² ARTS Lab (Advanced Robotics Technology and Systems Laboratory)

c/o Polo Sant'Anna Valdera, viale Rinaldo Piaggio 34, 56025 Pontedera (Pisa), Italy

Phone: +39-050-883400, fax: +39-050-883402

dario@mail-arts.sssup.it

³ INAIL RTR Centre

via Vetraia, 7 - 55049 Viareggio (LU), Italy

Phone: +39-0584-385376, fax: +39-0584-385359,

inail_rtr@mail-arts.sssup.it

Abstract. The recent advances of humanoid robotics led to achievements in the development of human-like body parts and whole bodies, as well as of perceptual systems and schemes for behavior planning and learning. For this reason, a step further can be envisaged in the application of human-like robots as experimental tools in neuroscience, for carrying on experiments that may be difficult or impossible with human beings.

This paper presents a human-like robotic manipulation platform for implementing neuro-physiological models of sensory-motor coordination in human grasping, with a particular attention to its sensory system. The proposed robotic system originates from requirements imposed by neurophysiological knowledge about the corresponding human system. Hence, it is composed of sensors and actuators replicating some level of anthropomorphism, in the physical structure and/or in the functionality. Software modules implement human-like basic mechanisms of perception and learning, on which more complex architectures are developed. The system is integrated so as to be as modular as possible and to be re-arranged for validating different hypotheses.

1. Introduction

In robotics, biology has been representing an inspiration source for the development of bio-mimetic components, as well as new control models, for biomorph robotic platforms. But the advances of robotics technology in the development of human-like components, i.e. sensors and actuators, is improving the opportunities of its application in the study of Man, as a tool for neurophysiologists, physiologists, neuroscientists, and psychologists, for validating biological models and for carrying on experiments that may be difficult or impossible with human beings. Therefore, the interaction between biological science and robotics becomes two-fold [1] (Figure 1): on one hand, biology provides the knowledge on the human system needed to build humanoid robots (or human-like components); on the other hand, anthropomorphic robots represent a helpful platform for experimental validation of theories and hypotheses formulated by scientists [2].

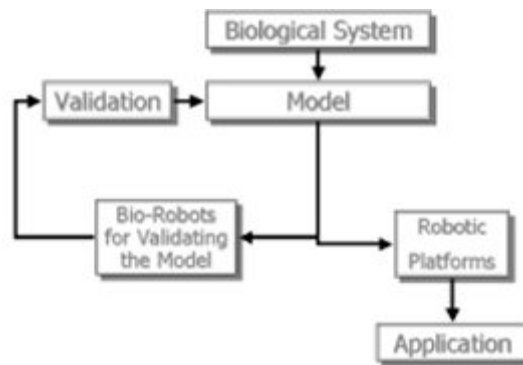


Figure 1. Relation between biological science and robotics.

The work presented in this paper is aimed at developing a robotic manipulation platform, which mimics human mechanisms of perception and action, and can implement neuro-physiological models of sensory-motor coordination. To this aim, an accurate analysis of neurophysiological works and above all a strict interaction with the neuroscientists have constituted the starting point for the hardware realisation of the robotic components.

In a biological system, a sensory system signals the state of the organism and of the surroundings, a musculoskeletal system translates forces into movements, and a CNS (Central Nervous System) links the two systems. A number of different components contribute to the task's complexity and particularly on the sensory side, signals from various sources (vision, hearing, touch, pain, perception) need to be integrated and interpreted [3, 4]. The redundancy of the motor system, both from the sensory viewpoint and from the muscular actuation viewpoint, is an important and desirable property as it allows the same motion to be carried out with different muscle combinations under different task-related and environmental circumstances.

In the functioning mode of a biological motor system, three basic mechanisms can be outlined [5]:

1. the selection of an appropriate action and the transformation of control signals from sensory to motor coordinate frameworks;
2. the coordination of the selected movement with other ongoing behaviors and with postural reflexes;
3. monitoring the movement to ensure its accuracy.

These three mechanisms require, to be accomplished, the development of internal models to allow the realization of the sensory-to-motor transformation as well as the motor-to-sensory transformation [5, 6].

In particular, the first transformation requires that sensory signals from the environment, from the reference inputs and possibly from the controlled object provide information on what actions have to be performed [6].

As regards the schemes for planning and learning, biological evidence points out the necessity of a parallel control structure between a feedforward action and a feedback action. In fact, in biological systems feedback control can cause instability in rapid movements due to the significant delay in the transmission of neural information [7-11].

The problem of excessive delay in the sensory information transmission can be present in robotic artefacts too, so new control solutions including feedback and feedforward loops are proposed in literature in order to ensure stability in low as well as fast movements (by feedforward) [6, 7] and to allow unskilled movements and interaction with the unknown environment by feedback [12, 13].

For instance, the robotic platform to be developed takes into account neurophysiological results on the organization and the functioning mode of human perception system as well as information from biology on the generation of human sensory-motor coordination for grasping, through mechanisms of planning and learning. Thus, the first step is the development of robotic components mimicking as much as possible biological systems; then, in a further step the implementation of human-like behavior mechanisms will be pursued.

Definitely, the system is composed of sensors and actuators replicating some level of anthropomorphism, in the physical structure and/or in the functionality. It is worth noting that their specifications are defined together with neurophysiologists, starting from:

on the neurophysiological side: definition of the robotic platform functionality (sensor modalities, features to be perceived, motor capabilities, control schemes, ideal tasks to be performed);

on the robotic side: description of the best available anthropomorphic robotic components (sensors, actuators, control schemes and systems, technology for new improvements), including demonstrations and tests.

The paper presents the basic features for a human-like robotic platform for manipulation tasks, by introducing in section 2 the requirements discussed and shared with neurophysiologists and by describing in details in section 3 the mechanics, the sensory system, and the functioning mode of the proposed hardware components to be integrated on the platform.

2. Neurophysiological Requirements

As natural, the best model for validating neurophysiological sensory-motor coordination schemes is the man with its motor and sensory apparatus. Hence, a general requirement for the development of a robotic platform replicating human-like behaviors is the anthropomorphism of its components.

In particular, as regards sensory-motor coordination control schemes for grasping and manipulation, the anthropomorphic model considered as reference is the human upper torso, including an arm, one hand, a head and the corresponding sensory apparatus.

Specifications for the actuators to be included in the platform (arm, hand, head) and requirements for the sensory systems arise from the literature and from discussions with neuroscientists and physiologists.

As regards the perception system, two basic apparatus were indicated as of paramount importance for the addressed applications:

- a somesthetic perception system, providing sensory information available on the actual state of arm and hand, usually related via proprioceptive and somatosensory signals;
- a visual apparatus, to give information on the extra-personal space, such as target location and other target and object properties derived from a visual base.

To understand what is the sensory apparatus mainly involved in the biological control of human actuators is one of the main target of this work. To this regard, the features of the biological actuators and of the sensory systems involved in the sensory-motor coordination are outlined.

The human arm can be modeled with a shoulder with at least 3 DOFs (DOFs), an elbow with 1 DOF and a wrist with 3 DOFs. Shoulder and elbow allow positioning the hand in the workspace, while the wrist allows defining the orientation of the hand [14].

The biological motor control for the arm requires proprioceptive information of the arm provided through the muscle spindle signals and the Golgi tendon organ signals.

For the hand, studies on the human hand and its functionalities show that at least 3 fingers are necessary to perform most human grasps [15]; hence the human model of the hand has to include at least the thumb, the index and the middle finger, with 3 DOFs for index and middle finger, and 4 DOFs for the thumb, and the proprioceptive and somatosensory apparatus. The physiological model of the somatosensory system consists of tactile FAI, FAII, SAI and SAII afferents signals [16], while the proprioception is analogous to the arm (i.e. information from muscle spindle and the Golgi tendon organ). The artificial sensory system should provide the following information:

- 1) contact making and breaking between object and fingertips;
- 2) contact making and breaking between hand-held object and environment;
- 3) the slip friction between object and fingertips;
- 4) the local shape at contact points;
- 5) the overall object shape;
- 6) the force vector at the contact point (tangential and normal force components).

Finally, as regards the human head, two main classes of movements have to be considered: eye movements and neck movements. The main eye movements in humans can be summarised in:

- saccadic eye movements: they are the rapid eye movements that change fixation from one target to another.
- pursuit eye movements: they are slow, smooth eye movements that enable one to follow a steadily moving target.

Eyes have a common tilt movement and independent pan movements allowing vergence. To approximate human eye range of motion, 120° should be achieved for the tilt and 60° for the pan movements.

Concerning the neck, four main movements are present [17,18]:

- flexion;
- extension;
- lateral bending;
- and axial rotation (supine position).

Finally, the visual apparatus is essential for recognition and pose estimation of parts of the human body, i.e. the hand and the arm, and of objects belonging to the surrounding environment.

3. Development of a human-like robotic platform

The previous analysis of neurophysiological specifications for motor as well as sensory apparatus has originated the design and the mechanical realization of the hardware components of a human-inspired robotic platform for manipulation. As announced above, the platform consists of:

- a 3 finger (thumb, index finger, middle finger) robotic hand (see Figure 2(a)), with 3 DOFs for each finger plus adduction/abduction for the thumb, and its somato-sensory system, which includes proprioceptive and tactile systems;

- a robotic head equipped with a stereoscopic vision system. The robotic head (see Figure 2(b)) has been purposely designed and developed in collaboration with a Japanese company, and comprises of 7 DOFs: 4 DOFs for the neck movements and 3 DOFs for the eyes (cameras) movements. The head is equipped with a retina-like vision system providing retina-like images;
- an anthropomorphic 8 DOFs robot arm, named DEXTER arm (see Figure 14), composed of a trunk with 2 DOFs, a shoulder with 2 DOFs, an elbow with 1 DOF and a wrist, characterized by 3 DOFs, and its proprioceptive sensory system.

In the following sections the basic characteristics of all the components will be discussed.

The robotic hand

The robotic hand evolved from a previous model of biomechatronic prosthetic hand, named RTR II [21,22]. It was designed in order to allow an independent motion of the three fingers and increase the number of active DOFs. The mechanics of the PALOMA hand consists of:

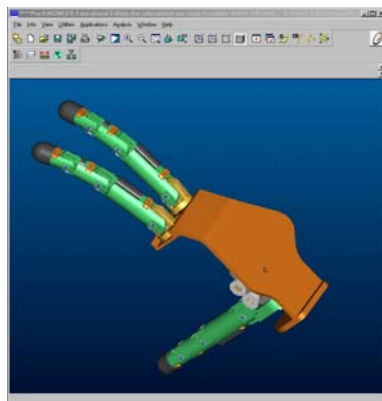
- 10 DOFs – 4 DOMs (degrees of motion) in total. The characteristics of the motors are showed in Table 1;
- underactuated fingers, each driven by a single cable actuated by a motor;
- one DOM for each finger (flexion/extension) + one DOM for thumb positioning (adduction/abduction);
- 9 Hall effect sensors (position), one for each finger joint;
- DC 6V motors and Encoders;
- The total weight is about 450 gr;
- The size is anthropomorphic.

| Type of movement and related finger | Device | Type- Model |
|---|-----------|-------------|
| Thumb adduction/abduction | motor | 1016G |
| | gearboxes | 10/1 |
| | encoders | 30B |
| Index, medium and thumb opening and closing | motor | 1727 C |
| | gearboxes | 16/7 |
| | encoders | IE2-512 |

Table 1. List of the actuation devices for the hand motor system

In particular, the hand mechanical structure shows several characteristics, such as:

- Three identical underactuated fingers with cylindrical phalanges (aluminium alloy);
- One 2 DOFs trapezo-metacarpal joint at the base of the palm which allows the thumb opposition movement towards the other 2 fingers;
- Compliant palm composed of 3 parts:
 - Outside shell: soft volar side (silicon rubber)+ rigid dorsal side (carbon fibre)
 - Inside aluminium frame: it holds the fingers, it contains the thumb abduction/adduction transmission chain and the trapezio-metacarpal joints of the passive ring and little fingers
 - Passive ring and little metacarpal that hollows the palm improving the grasp



(a)



(b)

Figure 2: CAD model (a) and picture of the prototype (b) of the artificial hand.

The robotic hand is based on the concept of underactuation, meaning that even if only 4 motors are present, the hand has 10 DOFs in total. The fingers can self-adapt to the object shape by using the passive DOFs by means of a differential mechanism integrated in the transmission system. The flexion/extension movements can be achieved independently by the 3 fingers and the thumb can also abduct and adduct. As a consequence the robotic hand is capable of the following functional grasps (Figure 3) [16]:

- the cylindrical palmar prehension;
- the prehension by subterminal-lateral opposition;
- the centralised grip;
- the tridigital grip;
- the prehension by subterminal opposition.

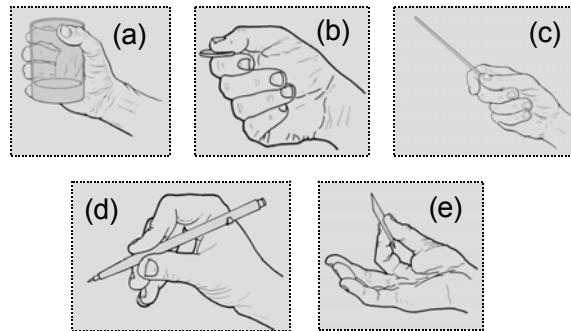


Figure 3: The expected functional grasps of the robotic hand: (a) the cylindrical palmar prehension; (b) the prehension by subterminal-lateral opposition; (c) the centralised grip; (d) the tridigital grip; (e) the prehension by subterminal opposition [16].

Moreover, the robotic hand can be considered anthropomorphic also in terms of weight and dimensions. The expected performance of the hand are the following:

- Maximum weight: 450 gr
- Maximum grasping force: 40 N (cylindrical)
- Maximum tip to tip force: 15 N
- Maximum closing time: 2 sec
- Trapezo-metacarpal thumb joint abduction/adduction range: 0° - 120°
- Finger joints flexion range: 0 - 90°

The proprioceptive and exteroceptive system

The proprioception on the robotic hand has been designed in order to provide the required information on all the phalanges of the hand. So, the solution consists of 9 joint position sensors (Hall effect sensor based) embedded in all the joints of each finger (Figure 4), and an incremental encoder on each motor. This choice allows both reading the position of all the phalanges during the tasks of grasping and manipulation through the Hall effect sensors and controlling the hand acting on the motors by exploiting the reading from the encoders. The joint position outputs return information on hand posture and on the approximate shape of the grasped objects.

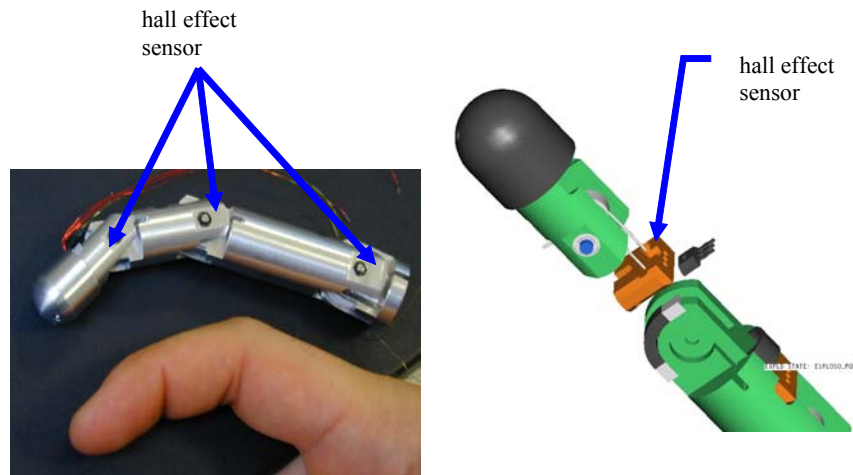


Figure 4. Positioning of the hall effect sensors

As the Golgi tendon organs give information on the tendon stretches, 3 tensiometers measure the tension on the cables controlling the fingers flexion (Figure 5).

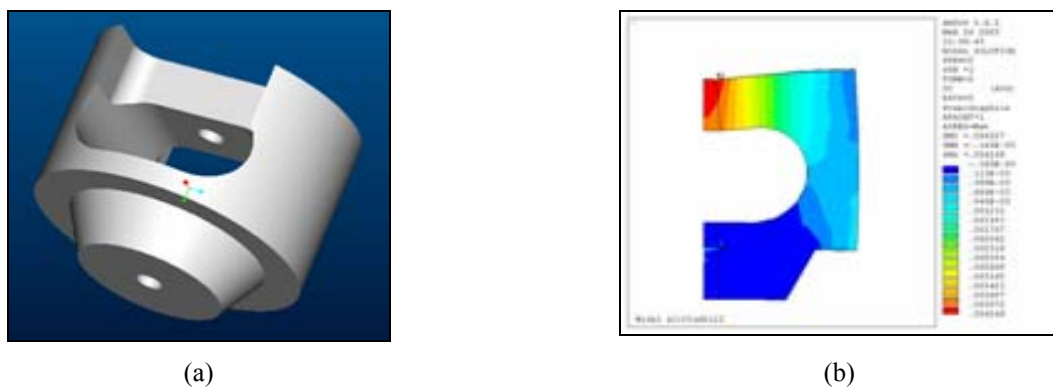


Figure 5. 3D model (a) and FEM optimization (b) of the tendon tensiometers mounted on the cables for controlling the finger flexions.

Finally, the contact of the hand and of the hand-held object with the environment is detected by means of an accelerometer integrated in the palm.

The somatosensory information are essentially tactile information. The idea developed was to distribute tactile sensors over the hand. It was realizable using two types of sensors, on-off touch sensors and 3-component force sensors.

On-off touch sensors are thought to be placed on the internal and lateral face of the phalanges and on the palm of the hand in order to sense the contact with the whole hand and to have a perception of the contact area. More sensitive on-off touch sensors will be placed on the hand dorsum in order to detect accidental contact with the environment. As regards the sensor design, it was thought to pose the on-off sensors on a flexible matrix in order to allow a uniform and closed distribution of the sensors as well as an easier disposition of the sensors on the phalanges (see Figure 6). The sensor distribution has been thought to replicate the fovea where the sensor density decreases starting from the most receptive area (fingertip) to the periphery (other phalanges and palm).

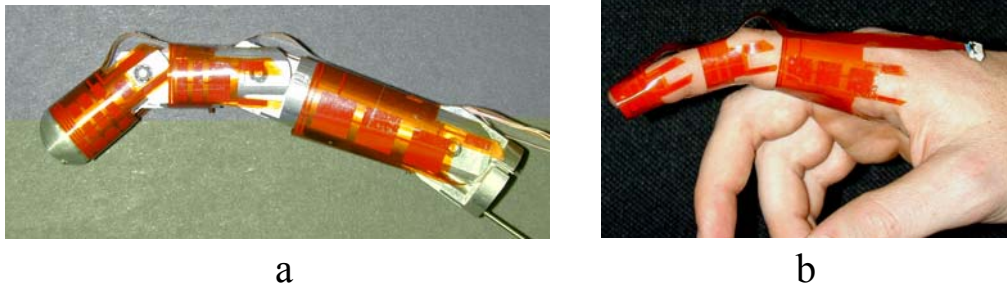


Figure 6: a) the contact sensor wrapper around the artificial phalanges and in b) comparing with those of the human hand.

In the somatosensory system design, the three components force sensors are to be mounted on the fingertips so as to measure the force vector at the contact point. Currently, two versions of the 3-component force sensor have been designed, in order to use initially the sensor that can be more rapidly realised and then replace it with the second more performing version.

The first version is a sensor based on a cross disposition of the strain-gauges and located at the base of the fingertip so as to make the whole fingertip a 3-component force sensor (see Figure 7).

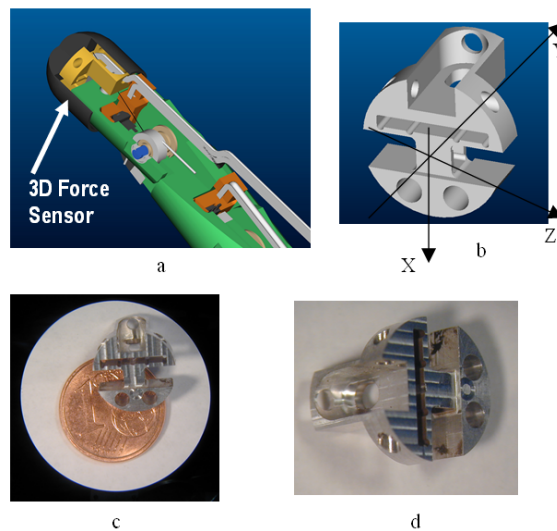


Figure 7: a) the 3D force sensor mounted in the fingertip of the index finger. b) the mechanics of the 3D sensors with the force reference frame. c) and d) show two images of the real sensor.

In the second version, the quantitative information (intensity and direction) about the force will be given by an array of three-component force silicon microsensors. A 2x2 array of silicon microsensors will be integrated on the fingertips as shown in Figure 8.

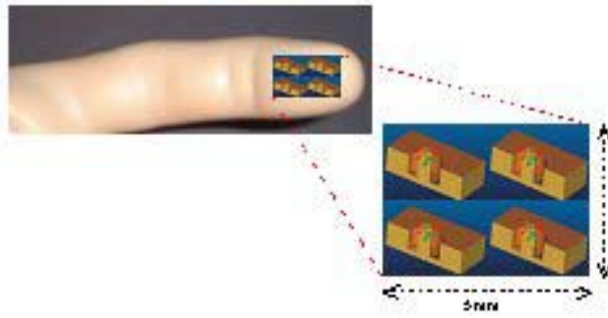


Figure 8: Fingertip Sensorization.

The single microsensors have been designed for a maximum force of 7 N and for normal and tangential working loads of 200-300 mN [23]. The theoretical values of the gauge factor and sensitivity are 162.8 and 6.1×10^{-3} mV/KPa for the normal force, respectively, while they are 63.8 and 0.013 mV/KPa for the tangential force.

The silicon microsensors are based on the piezoresistive effect and they exploit four piezoresistors that are ion-implanted in a silicon membrane and that will be used as independent strain gauges. The sensing element consists of a circular membrane with 4 tethers and a cylindrical mesa located in the center of the membrane (see Figure 9 and Figure 10). The particular 3D mechanical structure is obtained starting from an SOI wafer and exploiting a technological process of 52 steps that work the wafer from both sides by applying the STS ASETM technology [24,25].



Figure 9: Section of the sensor: 3D model (a) and SEM picture of implanted piezoresistors in one tether of the membrane (b).

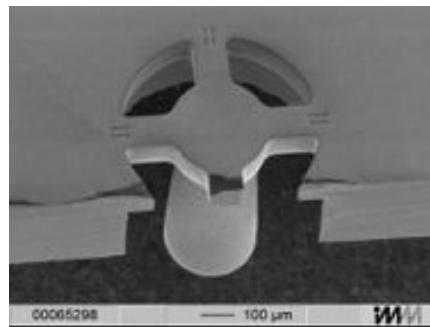


Figure 10: SEM picture of the cross section of silicon sensor mechanical structure; the picture is taken from the opposite side of the sensor modeled in Figure 9(a).

The sensor package presents requirements that depend on both the working principle of force sensor itself and the application in the robotic hand. Identifying side A and side B as shown in Figure 11, the physical interaction of the sensor with the outer world will be carried out through side B. Here the mobility of the piston (mesa on the membrane) must be allowed, limiting hysteresis and non-linearity effects, while assuring the structure protection. While side B performs the contact, side A is dedicated to the electrical connections coming out horizontally from the package. Moreover, a rigid structure with external flat surface is needed to support the sensor and position it on the finger surface. Starting from these requirements, for the electrical part of the package the connections will be performed via a polymer flip-chip bonding technique (Figure 11(a)) To this aim, a silicon substrate (support wafer) with Al metalizations and Au pads will be used.

Sensors will be assembled in a flexible package by using an array configuration as modelled in Figure 11(b). The sensors will be silicon islands embedded in a polymeric matrix (kapton, polyurethane). Figure 11(b) shows an array of 2x2 sensors with the metalizations embedded in the flexible strip to connect the sensors to outer circuitry.

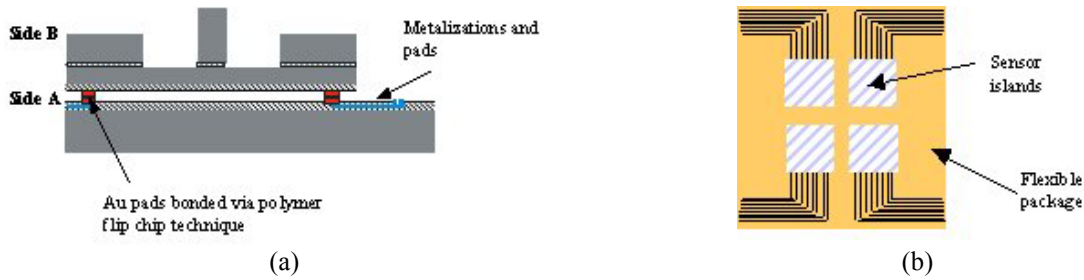


Figure 11: Schematization of electrical package (a). Model of 2x2 array of silicon microsensors (b).

The robotic head

The mechanical structure and the performance of the robotic head (Figure 12) have been designed based on the model and performance of human head in terms of DOFs, ranges of motion, speeds and accelerations. The resulting head has a total of 7 DOFs: 4 f.o.f. on the neck (1 yaw, 2 pitches at different heights, 1 roll), 1 DOFs for a common eye tilt movement and 2 DOFs for independent eye pan movements.

The 2 DOFs performing pan movement of the eye permit vergence of the two cameras, thus allowing foveation of targets. The performance of the head allows also performing pursuit movements as well as saccadic eye movements like in humans. The head is equipped with incremental encoders for measuring the positions of all the joints as proprioceptive information.



Figure 12: Picture of the anthropomorphic head and DOF disposition.

The mechanical design of the head includes the 7 DOFs, whose range of motion, speeds and acceleration are reported in Table 2.

| | Range of Motion | Speed | Acceleration | Resolution |
|------------------|-----------------|--------|------------------------|------------|
| Yaw | ± 80 | 160°/s | | |
| Roll | ± 45 | 160°/s | | |
| Upper Pitch | ± 45 | 160°/s | | |
| Lower Pitch | +30/-45, | 160°/s | 12.000°/s ² | 0.003° |
| Eye Pitch Axis | ± 45 | 600°/s | 12.000°/s ² | 0.003° |
| Eye R/L Yaw Axis | ± 45 | 600°/s | 12.000°/s ² | 0.003° |

Table 2: Technical Specification of the Robotic Head.

As regards the vision system, in order to focus the anthropomorphism requirements, a retina-like vision system will be integrated on the robotic head. It is based on a space variant visual sensor whose resolution is higher in the centre (fovea) and degrades towards periphery, as an imitation of human retina (see Figure 13). In particular, The arrangement of photosites is based on a log-polar structure: a constant number of receptors (252) is arranged along 110 concentric circles, with decreasing width from the periphery to the center; in the central area of 42 rings, named fovea, the number of photosites is decreased by 6 in each ring. Thus, these cameras have a total of 33193 pixels, 110 rings with 252 pixels in the periphery and 42 rings with a number of pixels decreasing toward the center in the fovea, corresponding to a standard image of 1090 x 1090 pixels.

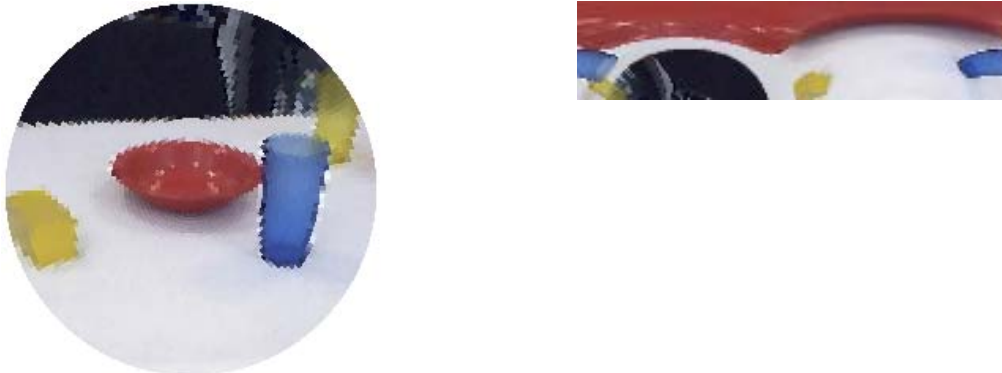


Figure 13: Example of retina-like image (a) and the corresponding cortical image (b).

The main advantage of this kind of sensors is that the amount of data is drastically reduced and faster processing can be achieved, provided that the eyes are moved in a continuous tracking of the points of interest, as it happens in humans.

The use of retina-like cameras can help reduce the computational cost, and consequently time, because the amount of data in a retina-like image is much smaller, still giving significant information on the same field of view. This allow to include some visual processing in the control loop of the head and eye movements.

On the other hand, retina-like cameras needs very fast and accurate movements in order to focus the points of interest and allow their good vision. Therefore, it is crucial that they are mounted on a robotic head able to fast and precisely move them.

The robot arm

The robotic arm integrated in the platform is an 8 DOFs robot arm, named Dexter and developed by S. M. Scienza Machinale srl, Pisa, Italy, as an assistive robot.

Its physical structure is highly anthropomorphic (see Figure 14), with the link arrangement reproducing the human body from trunk to wrist. In fact, a trunk, a shoulder, an elbow and a wrist can be identified in the Dexter kinematic structure and, as a consequence, human movements in the interaction with the environment can be easily mimicked. The redundancy of the kinematic structure of the arm facilitates dexterous manipulation, enables the arm to be configured for work at various heights above the ground, and allows the arm to fold so that its work envelope can

be minimized. Particularly, the redundancy allows the arm to turn around its torso and move the elbow from a frontal to a side position like a real human arm.



Figure 14: the DEXTER robot arm.

So, briefly, the Dexter arm has 8 revolution joints actuated through pulleys and steel cables in order to make the mechanical structure light and flexible and to allow the joint masses to decrease from the first link to the last. All that contributes to enforce the similarity with the human arm.

As already mentioned, the mechanical transmission system is realised through steel cables, which allow the 6 distal motors to be located on the first link, which represents the trunk, by achieving low weight and low inertia for the distal joints. The first two proximal joints are aimed at pre-positioning the distal 6 DOFs manipulator so as to increase the overall workspace.

Moreover, like a human arm, the proximal joints are responsible for the correct positioning of the end effector in the free space and the last joints (i.e. the wrist) are more involved in the regulation of the orientation.

The proprioceptive information on the position of all the joints are provided by incremental encoders located on each motor.

The anthropomorphism of the robotic arm is of paramount importance from the hardware viewpoint of the aimed robotic platform, but also adequate control schemes need to be developed in order to enhance its performance in the interaction with humans.

The arm actually can be controlled through a standard stiff PID controller as well as through interaction controls with self-adjusting compliance [19]. Furthermore, new control schemes have been developing, aimed at implementing biomorphic control mechanisms based on the combination of a feedforward control loop with a feedback control loop. In particular the biological mechanism of co-activation between the alpha and gamma motoneurons is studied as a useful means to regulate the visco-elastic properties of a robot arm [20].

4. Conclusions

The paper proposes the application of robotics in the study of Man, by providing artificial platforms for validating neurophysiological models. The authors propose a work on the development of an anthropomorphic robotic platform for sensory-motor coordination in human grasping and inspired by the analysis of neurophysiological specifications for the human actuators and sensory systems.

The components of the artificial platform are presented in detail by emphasizing the parallel with the human systems used for inspiration.

Once integrated, the platform will be used for implementing a multinet architecture correlating sensory and motor signals and for validating a 5-step model of progressive learning mimicked by human babies.

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