A biomimetic upper body for humanoids

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Summary / Abstract

Developing a humanoid robot is not adding intelligence to any mechanical solution; in our opinion it is developing together" body and mind" of the robot to obtain a system intrinsically able to adapt to real situations and to share the same solutions of the human user. In this paper we present the main architectural solutions of our humanoid robot. In particular we describe its unique mechanical construction, fully based on McKibben actuators. Starting from a biomimetic design, we will explain the controlling strategy and discuss about performance.

1 Introduction

Classical industrial manipulators have reached a great effectiveness. Nevertheless the human arm is superior; it is lighter and has a better force under weight ratio.

Our project is about the study and the development of techniques devoted to the design of hardware and software components for improving humanoid robotics and providing users of tools for using those robots in various autonomous or cooperative ways.

Our aim is to develop the methods that could transfer to humanoid robotics the results already available in autonomous robotics. We want to span a large spectrum of approaches, from biomimetic to reactive and to cognitive models, and integrate them in more advanced and flexible systems.

Our first challenge is to advance those techniques, so to make them available on humanoid robots and be able evaluate how much the approaches inspired from nature give more robust and performing systems.

A second challenge is the extension of methods developed for autonomous or for industrial robots to humanoids robotics, to put them in real action for assistance and cooperation with other robots and humans.

Developing a humanoid robot is not adding intelligence to any mechanical solution; in our opinion it is developing together" body and mind" of the robot to obtain a system intrinsically able to adapt to real situations and to share the same solutions of the human user.

A humanoid robot, in order to mimic the human morphology and functionality, needs a complex kinematic structure. Since in the human body we have more than one hundred degrees of freedom, a humanoid robots needs in theory one hundred actuators, and a double number of sensors to sense position and force in each actuator. Moreover, it is extremely important in a humanoid robot to control the joint compliance in order to allow a safe collaboration with the human beings. In this situation the classical control systems [9], based on the accurate knowledge of the process dynamic model, are not usable. This observation is even stronger if the robot to control is composed by actuators light and with a high power to weight ratio, like McKibben pneumatic artificial muscles [11], or electro active polymers (EAP). These devices tend to change their behaviour when the number of working cycles increases, therefore a classical PID controller is not able to maintain the initial performance and an adaptable control system is needed.

The control system strategy and the mechanics proposed in this paper have been designed for our prototype of upper torso, derived from Maximum1 [3], illustrated in Figure 1, and fully developed at Politecnico di Milano.

Figure 1 The upper body robot, developed after the Maximum1 arm.

Maximum1 has been designed using the paradigm of the bio-robotics [12], the main idea being to use the knowledge about anatomy and physiology of the human limbs to obtain a system with comparable performance in motion. The system has been designed on the basis of anatomical studies of the human limb. Our robot differs in many aspects from other similar system: it has seven dof in the arm built with special solutions for the joints, it is moved by pneumatic artificial muscles, it is made of light materials, and it has an under-actuated human like hand.

The robot should be able to manipulate common objects. We are not talking here about the classical approach to robot grasping that requires a dynamic analysis of the object and the hand. Our hypothesis is that a strict coordination of hand and vision will allow finding the apt kind of grasp configuration, then the inverse-kinematics will find the target for the joints positions, and the target be reached by the low level controller in the robot. This approach will be useful also to apply imitation learning to the hand movements.

To build a biologically inspired control we consider two levels: the high level which is responsible for defining the motor patterns or primitives, and the low level which is based on the moto-neurons and implements the reflexes. Both the levels can integrate some learning capability; however only the high level learning has been developed in modern artificial systems.

Albus [1] started this kind of research on the consideration that the cerebellum is responsible for coordination and temporization of the muscular activity to obtain the basic motions. In fact the spinal system is able to learn the basic motion actions and to adapt them to the external conditions. Kawato [7] from the evidence of neurophysiology experiments claims that the optimal control of the arm is based on an internal representation of the dynamic model of the skeleton and muscular systems. In fact the rapid movements (150-500 ms) are not compatible with the delay of the visual feedback (150-250 ms. In conclusion, the inverse dynamic model is learned by the encephalon and is used to control the movements in a Feed Forward strategy.

The reflexes arcs are our low level controller, as already proposed in [6]and discussed in [2, 3]; they are able to reproduce the arc on an artificial device to maintain its position and control its stiffness.

Other robots can show similar characteristics in the bio-inspiration, as the one illustrated in [11]; however their controller is really different.

In the following sections we will present the mechanical structure of our robot, its control strategies, and the obtained results.

2 Mechanical structure and actuators

Our robot consists of a sensor head for visual perception of the environment, an upper body with one arm with a large range of motion, and a neck. The size of the design space and the motion space are similar to that of a human person with a height of approximately 170 cm.

The arm has seven degrees of freedom; the hand has 15 underactuated dof. Compared with other humanoid robots, the arm provides large and humanlike ranges of motion. The neck joint with three degrees of freedom allows humanlike motion of the head.

2.1 Mechanical design

The upper arm is actuated by seven linear artificial muscles that control the three degrees of freedom of the shoulder and the one of the elbow. The wrist has three degrees of freedom actuated through five muscles. The neck has three degrees of freedom. The hand has five fingers that are actuated as three independent fingers.

The artificial muscles are used in the common protagonist/antagonist organization. The muscles are connected to the links by flexible tendons that allow the actuator to change its orientation according to the links direction.

2.1.1 Shoulder and elbow

The upper arm is composed by three links in aluminium and two articulations.

The shoulder joint, with 3 dof, is moved by five artificial muscles: Deltoid, Pectoral, Dorsal, Supraspinatus, and Subscapularis. The synergy of Deltoid, Pectoral and Dorsal actuators allows the upper arm flexion-extension and adduction-abduction. The Supraspinatus and Subscapularis instead act to rotate the upper arm around its longitudinal axis. Thanks to a special design for the shoulder this third degree of freedom is cinematically independent from the first two [4, 5].

In Table 1, 2 and 3 we give the characteristics of links, the joint ranges, and the muscles.

Table 1 – links in the arm

links	length	section	Mass
upper arm	38 cm	100 mm²	0.21 Kg
lower arm	144 mm	100 mm²	50 g
wrist	96 mm	1133 mm²	70g

Table 2 – ranges of the joints in the arm

joint	rot X	rot Y	rot Z
shoulder	0° - 150°	0° - 150°	0° - 90°
elbow	0° - 120°	0° - 0°	0° - 0°

Table 3 – muscles in the upper arm

actuator	length	Mass	Contraction
Biceps	26-22 cm	30g	15.4 %
Triceps	23.5-19.5cm	40g	17%
Subscapularis	30-28 cm	30g	7 %
Supraspinatus	24-20 cm	30g	16.4 %
Pectoral	40-33 cm	30g	17.5 %
Deltoid	33-27.5 cm	30g	16.4 %
Dorsal	44.5-36 cm	40g	19.1 %

In Figure 2 we see details about the joints of the upper arm, namely shoulder and elbow, and in Figure 3 how they are moved by the actuators.

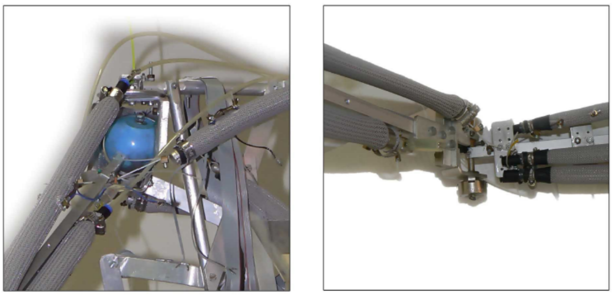

Figure 2 The shoulder and elbow joints

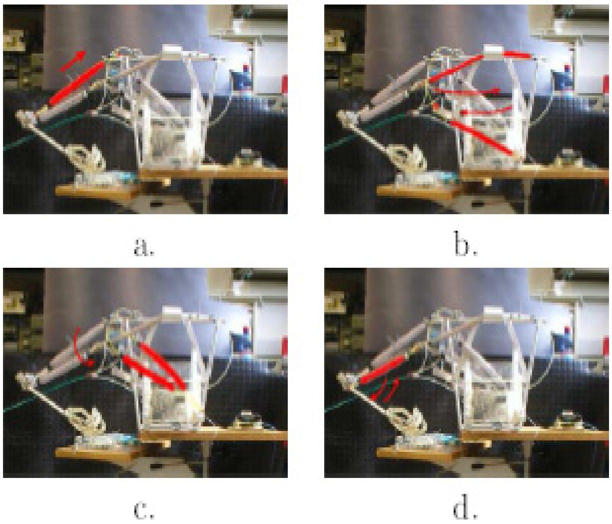

Figure 3 The shoulder and elbow joints actuated. (a) Deltoid lifts the shoulder; (b) Pectoral and Dorsal allow adduction and abduction, (c) Supraspinatus and Subscapularis allow shoulder rotation , (d) Biceps and Triceps move the elbow.

2.1.2 Wrist

A few studies have been done on modelling the human wrist for antropomorphic robots [10].

The human wrist is not a single joint, but consists of multiple joints. It contains eight small carpal bones, arranged in two rows, proximal and distal. The distal row articulates with the five metacarpal. The proximal row articulates with the two bones of the forearm, the radius (on the thumb side of the wrist) and ulna (on the little finger side.) In addition, the distal radius and ulna articulate with each other, so the radius and ulna can rotate around each other, so that the forearm can be pronated (palm downward) and supinated (palm upward).

The movements of the other wrist joints together produce the wrist movements of flexion (bending toward the palm) and extension (bending backward), abduction (bending toward the radial side), and adduction (bending toward the ulnar side.

In Figure 4 we see the mechanical structure of the wrist.

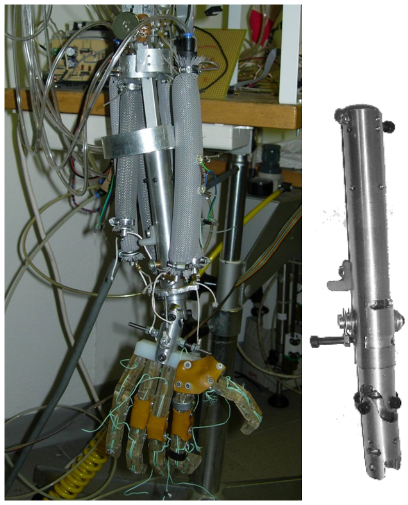

Figure 4 The mechanics of the wrist incorporated in the lower arm.

In our wrist the prono/supination movement is obtained with a simplification of the anatomic structure; we developed a single bone made of two coaxial cylinders, where the inside one can rotate with respect to the outside one. Here the actuation is obtained using one muscle and one spring. Flexion/extension and deviations are obtained using a cardan joint actuated by 4 muscles.

In Table 4 we compare the human ranges and the obtained ranges of angular movements in the wrist; Table 5 gives the details of the muscles.

Table 4 – ranges of the wrist angles

Movement	Human range	Experimental
Pronation	180°	95°
Flexion	85°	50°
Extension	85°	65°
Adduction	45°	45°
Abduction	15°	21°

Table 5 – muscles of the wrist

actuator	Length max-min	Contraction
Pronator	12-8.8 cm	26.67 %
Flexor	19.6-15.0 cm	23.47%
Extensor	19.4 -14.8cm	23.71 %
Adductor	18.2 -14.7cm	19.23 %
Abductor	18.5 -15.1cm	17.78 %

2.1.3 Hand

The robotic hand "whitefingers", illustrated in Figure 5, has been developed with the aim to make simple its construction. All the pieces are cut from a polycarbonate sheet, and the movement is transmitted through tendons. The hand has 5 fingers with 3 dof each, a thumb with 4 dof, a fixed palm; no adduction/abduction of the fingers is possible.

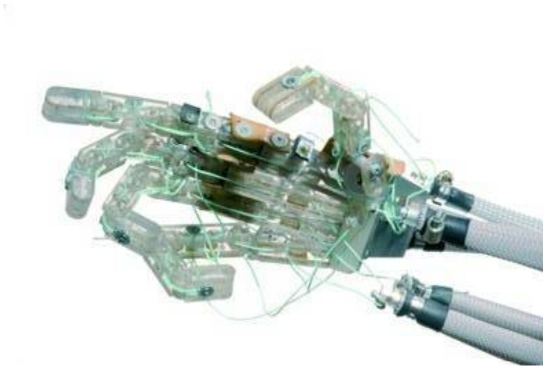

Figure 5 The robot hand whitefingers

Details about the controller of the hand are given in [2].The hand is under-actuated, so the last three fingers are moved together by a couple of artificial muscles.

2.1.4 Neck

The complex kinematics of the human neck is defined by seven cervical vertebrae. Each connection between two vertebrae can be seen as a joint with three degrees of freedom.

For our robot, the kinematics of the neck has been reduced to three rotational degrees of freedom. Two degrees of freedom allow the neck to lean forwards and backwards and to both sides, another degree of freedom allows nodding of the head.

The neck is built from a flexible tube actuated by five muscles organized as the principal muscles of the human neck. It combines the three dof of the neck and reaches ranges quite similar to the human ones. It will support the head (not yet attached).

Figure 6 shows the reference system of the neck, the organization of the muscles, and the physical implementation of the prototype. Table 6 gives the ranges of the movements obtained.

Table 6 – angular ranges of the neck movements

Movement	ranges
Frontal flexion	36°
Frontal extension	-75°
Lateral flexion dx	40°
Lateral flexion sx	-40°
Rotation dx	-38°
Rotation sx	38°

The head is still under development. It integrates two cameras with two dof each, and allows human like motions of the eyes as well as convergence.

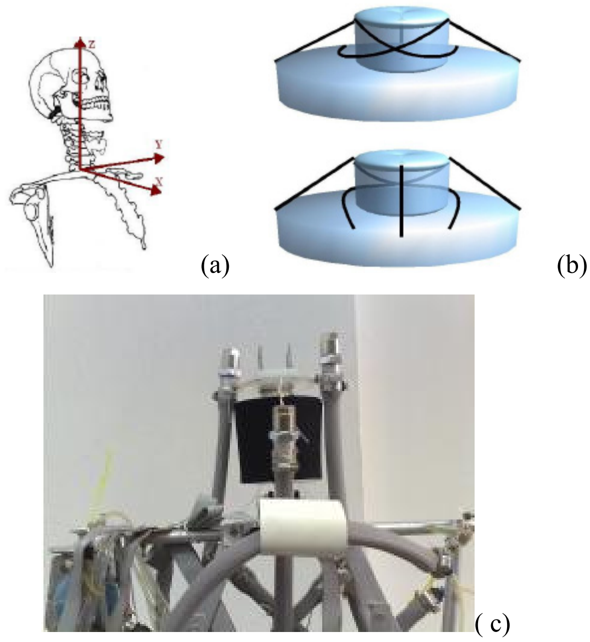

Figure 6 The neck – (a) The reference system; (b) the five muscles of the neck (back and front view); (c) the real implementation.

2.2 Actuation system

We chose pneumatic McKibben actuators for several reasons. They are efficient, since an actuator of 10 grams can develop a force of 200N; they are intrinsically elastic, so their use increases the safeness of the robot and facilitates the stiffness regulation. Furthermore they mimic the human muscle at least from the macroscopic point of view.

Of course this kind of actuators brings also problems, since their dynamic behaviour is not linear and they are subject to hysteresis that complicates the control strategy and decreases the system precision [2].

Each muscle has been expressly manufactured and equipped with a force sensor (a strain gauge in series comparable in function to a Golgi tendon organ), and a position sensor (a Flex sensor in parallel comparable to a muscle spindle in the natural muscle). See in Figure 7 a typical muscle.

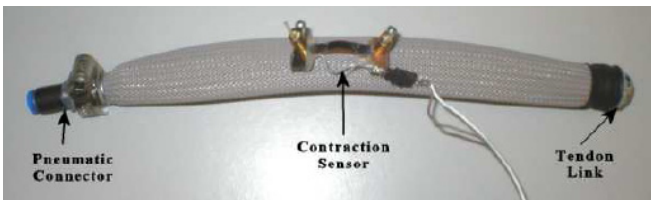

Figure 7 The muscle equipped with position sensor

A potentiometer is inserted in the elbow, so the biceps and triceps muscles do not incorporate the position sensors.

Sensor signals are conditioned and gathered by dedicated boards and sent to the A/D card in a PC. The control system runs in real time in a target PC, and its output is converted in the signals that command the actuators.

In order to control the McKibben actuators we developed a simplified formula that explains the static behaviour of the actuator. The force F is computed as in equation 1:

$$F(\epsilon, P) = (\pi r_0^2) P [a(1-\varepsilon)^2 - b] \qquad (1)$$

from inside pressure, length, and parameters.

The rate of contraction ε is defined as in equation 2:

$$\varepsilon = \frac{l_0 - l}{l_0} \qquad (2)$$

The maximum force is generated when ε is zero. When the actuator is completely contracted (20% of its length) the force generated is 0.

3 Kinematic models

The direct kinematic model of the robot has been built using a classical DH formulation. We see in Figure 8 the refernce systems considered for manipulation.

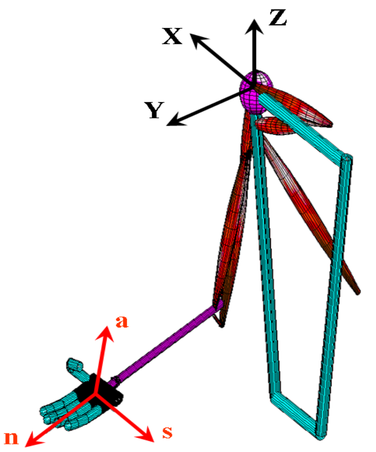

Figure 8 The absolute system is in the shoulder, and the hand system in the palm.

The inverse kinematics problem is a crucial issue for every manipulation system. If the robot has a complex or redundant kinematics, it could be very difficult to find an analytical solution, and if the kinematic chain is redundant it is also necessary to discriminate one of the many available solutions. Another issue is the presence of singularity points inside the workspace; in this case the Jacobian matrix cannot be inverted and consequently it introduces discontinuities in the joint workspace, so that a continuous trajectory in the Cartesian space has a discontinuous one in the joint workspace. When this happens the robot may change its posture very rapidly, representing a danger both for its integrity and the human operators near to it.

Furthermore in a robot arm with an anthropomorphous architecture open kinematics chains are combined with closed ones, and this normally complicates the solution also for the direct kinematis. The solution of the direct kinematics for a parallel robot requires to verify if the combination for the joint positions is admissible, and this usually requires to solve a systems of non linear equations. It becomes therefore necessary to adapt and combine classical techniques to reach a good tradeoff between precision real time performances, and singularities avoiding [5].

Our approach to solve the inverse kinematics is based on the fast descent gradient algorithm in combination with an autoregressive method to choose the next step of descent. Furthermore to avoid local minima we adopted the simulated annealing technique.

The IK algorithm we implemented allows both computing the joint angles and the actuators length to obtain the defined position. In fact the possibility of reaching a given position in the Cartesian space can be verified in the joint space, but the real actuation in the actuator space can find other limitations. For this reason the best is to compute directly the muscle lenghts that will take the hand to the fiinal position.

We separately solve the wrist position and the hand orientation. The wrist position can be solved with the equations presented in [5], and the hand orientation is solved in a similar way, starting from the wrist position. The Algorithm of the gradient descent is in Table 7.

The rotations defining hand orientation are in equation 3:

$$\mathbf{R}^0_{\alpha,\beta,\gamma} = \begin{bmatrix} \cos\alpha & 0 & \sin\alpha & 0 \\ 0 & 1 & 0 & 0 \\ -\sin\alpha & 0 & \cos\alpha & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\beta & -\sin\beta & 0 \\ 0 & \sin\beta & \cos\beta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} \cos\gamma & -\sin\gamma & 0 & 0 \\ \sin\gamma & \cos\gamma & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad (3)$$

The solution of the wrist is easily done using the joint angles insteads of the muscle lenghts. For each movement (flexion or extension, adduction or abduction, pronation) only one muscle is active at a time, so the joint solution can be easily transformed into the actuator lengths. The rotation defining the hand orientation are in equation 3:

Table 7 – The IK algorithm

```
Descent method
        -Set Current Orientation
        -Set Target Orientation
        -Calculate
        while (ΔO(q)> εmax  and  step<maxstep )
           for each muscle belonging Sub(i)
             - Decrease its length
             - Calculate the effect on end-effector(DK)
             - Calculate ΔO(q)
             - Calculate Gradient
               - Calculate Muscle Velocity
               if  (ΔO(q) decreases  update muscle length
          end
           end
            - Increase step
        end
```

The solution of the neck is obtained using a standard DH notation on a simplified model. However for the implentation we have found a linear relation between the Cartesian coordinates of the neck endpoint and the actuators length, so kinematic equations can to be solved at run time using a table lookup.

4 Reflex control strategy

The control system of the arm is organized in a modular and hierarchical fashion.

- High level controller: contains the Inverse Kinematics and Tajectory generation
- Medium level controller: contains the path generation
- Low level controller: contains the reflex modules and the control of the muscles.

The signals transmitted from one module to another are expressed as vectors (each component corresponds to a muscle). Lt represent the target length of an actuator, Vt the target velocity, P the stiffness, E the error.

At the bottom level there are the artificial reflex modules that govern the actuator's contraction and force. These modules receive inputs from the joint path generator, which in turn is fed by the inverse kinematic module that computes the target actuators lengths. The inputs of the entire control system are: the final hand position in the Cartesian space, and a signal that scales the level of co-activation of the artificial muscles that govern the same joint.

Reflex behaviours are accomplished by different modules that implement a simplified model of the natural circuits present in the spinal cord. Each module is dedicated to the control of the muscles that govern shoulder, elbow, and wrist.

Since the artificial muscle is constituted by only one functional fibre the biological organization of the natural muscle in motor units is neglected in our model. The artificial muscle activity is therefore regulated by a single motoneuron. The same consideration can be done also for the sensorial system in the muscle that in this case is constituted by only one artificial spindle organ and only one artificial Golgi tendon organ.

With respect to other models in literature we decided to neglect the spike behaviour of the motoneurons; instead we concentrated our attention on modelling its membrane potential. Each motoneuron receives inputs from almost all the cells that compose the circuit. Its outputs set the actuators pressures. We developed the dynamic equations of the neurons from literature.

The reflex module that governs the muscles implements an opponent force controller whose purposes are to provide inputs for the path generator module, to measure movement's error, and to return error signals when the execution is different from the desired movement.

The control of the joint's stiffness is very important during the execution of a certain task with the robot's arm. Humans usually can reduce or increase the joint stiffness when they are performing a certain task. For example catching a heavy object that is moving fast requires high stiffness of the lower and upper body articulations, while making a caress to someone requires a low stiffness. The articulation's stiffness, in turn, is regulated by the muscle co contraction. In the reflex modules the stiffness is regulated by signals that excite the interneurons.

Both myotatic and inverse myotatic reflexes are implemented, as illustrated in [3]. Figure 9 shows in detail the neuron architecture for the elbow joint. M6 and M7 are the motoneurons that control the contraction rate and force of triceps in biceps. I are the interneurons that receive the error signal from force sensors. In the reflex module the stiffness is regulated by the P signals that exite the I interneurons.

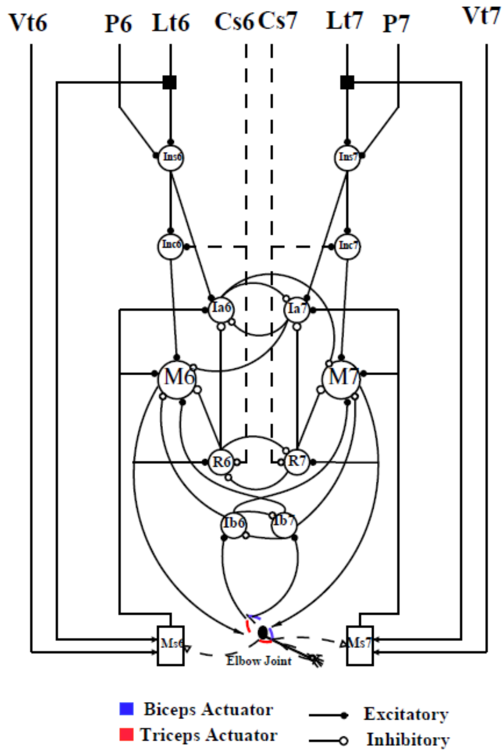

Figure 9 The reflex controller of the elbow, with motoneurons, interneurons, and signals.

We developed another classical architecture to independently control each actuator using a PID controller for the neck and the wrist, with adequate results. We will check the results against the reflex controller in further studies.

5 Implementation of the controller

The control system has been implemented in Matlab 7.0 and Simulink. The software runs on a host PC, where the trajectories are computed; the host PC is interfaced to a target PC where the operating system xPC-Target runs.

The control system on the PC receives and elaborates trajectories via RS-232 serial connection and sends back its output, through the Target-PC, to the electro-valves module that has the main purpose to set the actuators pressures. This module is equipped with micro solenoid-valves that can operate at a maximum frequency of 20Hz. Using a PWM (Pulse Wide Modulation) modulation it is possible to regulate the air flow that feeds the single actuator and therefore its force and position.

Figure 10 shows the hardware architecture.

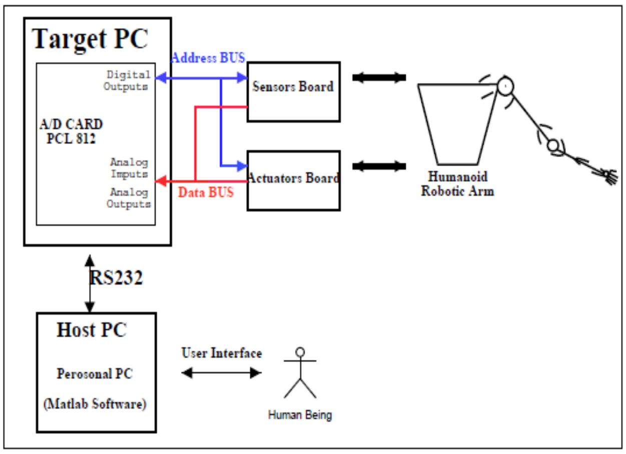

Figure 10 Hardware architecture

An important capability of a robot arm cooperating with humans is the ability to follow a trajectory inCartesian space. We have experimented the capability to follow simple trajectories (linear and circular) through our simulator, where we input a trajectory in the Cartesian space and obtain the values of the muscle lengths.

As an example, we show in Figure 11 the muscle movements and the robot posture during the execution of a circumference on a plane parallel to the z-y plane, and with a diameter of 12 cm.

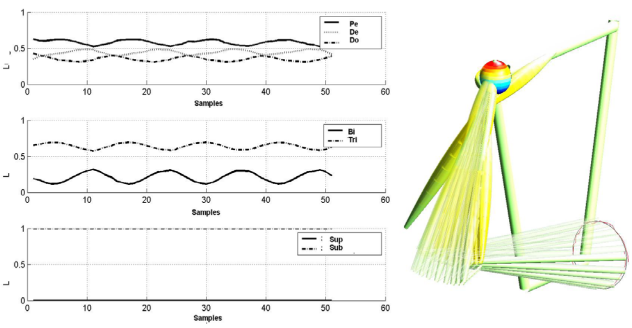

Figure 11 Normalized actuator lengths for a circular trajectory with center (-5,20,-30)

The same results have been checked on the real robot, demonstrating a good capability in following trajectories in Cartesian space.

Another set of experiments has been done to evaluate the robot performance in terms of work space.

To check the range of the movements on the hardware, we made extensive experiments. In Figure 12 we seefor instance the angular ranges of the wrist movements, that are similar to the human ones. However, in pronation the resulting range is smaller than in humans, due to the different mechanical solution adopted (a rotation inside a cylinder and not two bones articulated at the elbow).

Similar experiments have been carried out on the whole structure, showing some limitation in the work space with respect to the human movement ranges; this limitation derives from the mechanical constraints during the assembly. However they compare well with the target values.

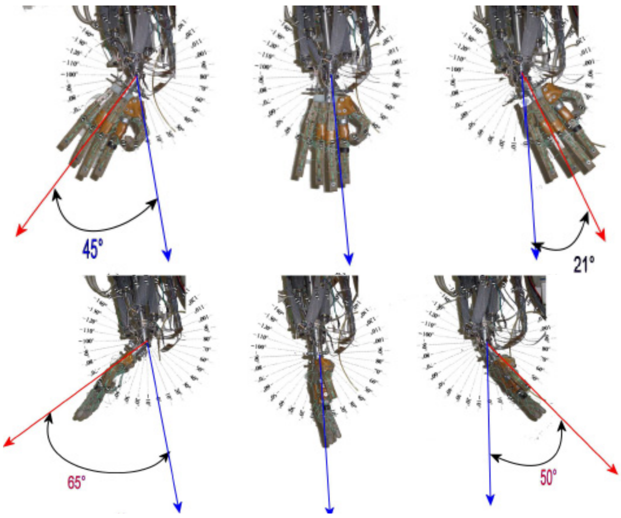

Figure 12 Up: Ranges of wrist adduction and abduction; Down: Ranges of wrist flexion and extension.

6 Conclusions

During the last years we developed a humanoid robot with an anthropomorphic structure of the torso, to experiment in cognitive and humanoid robotics.

The prototype so far built has some unique characteristics that make it compatible with morphology and organization of the human limb.

In particular we developed an actuation system that emulates the arrangement of the human musculature, and a control system that is organized in a modular and hierarchical way. The high level controller is charged to generate the arm trajectory and to perform the inverse kinematic; the low level controller sets the muscles lengths and the joints stiffness.

In order to perform the inverse kinematics we used the gradient descent method, to calculate the minimum of the distance function between the current and the target wrist position. Results show that the arm can perform different kind of trajectories allowing also regulating, during the movement execution, the joint stiffness. This is very important especially for the execution of specific tasks in collaboration with human beings.

We are working now on defining a neural model also to model the visual cortex. Our final aim will be to demonstrate cognitive capabilities in integrating hand motion and vision [8].

The development of a compliant outer skin with tactile sensors in the hand is another active area of research on our robot.

7 Literature

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