A NEURAL-CONTROL SYSTEM FOR A HUMANOID ARTIFICIAL ARM

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Abstract: In this paper we illustrate the architecture and the main features of a bio-inspired control system employed to govern an anthropomorphic artificial Arm. The manipulation system we developed was designed starting from a deeply study of the human limb from the anatomical, physiological and neurological point of view. In accordance with the general view of the Biorobotics field we try to replicate the structure and the functionalities of the natural limb. Thanks to this biomimetic approach we obtained a system that can perform movements similar to those of the natural limb.

The control system is organized in a hierarchical way. The low level controller emulates the neural circuits located in the human spinal cord and is charged to reproduce the reflexes behaviors and to control the arm stiffness. The high level control system generates the arm trajectory performing the inverse kinematics and furnishing the instantaneous muscles reference position. In particular we implemented the Inverse kinematic using a gradient based algorithm; at each step the actuators movements are arranged in order to decrease the distance between the wrist and the target position.

Simulation and experimental results shows the ability of the control system in governing the arm to follow a predefined trajectory and to perform human like reflexes behaviors.

1 INTRODUCTION

Robotics since from the beginning was involved in replicating the human manipulation capabilities. One of the first manipulators, designed for research purposes, was the Stanford Arm (Stanford Artificial Intelligence Laboratory). This robot was furnished of 6 DOFs (Degree Of Freedom), five revolute joints and one prismatic. Even if the mechanical architecture was thought with the aim to emulate the human movements we can not consider it as a real anthropomorphic system.

In sixties General Motor (the first to employ a Manipulator in an industrial process) financed a research program at MIT to developed another well know robotics arm: the PUMA (Programmable Universal Manipulator for assembly).
We can classify this manipulator as anthropomorphic, indeed it is possible to compare it to a human arm. At first we can divide the mechanical structure in three principal blocks: the shoulder with two DOF, the elbow with 1 DOF and the wrist with another three DOF. The Puma has a dexterity that is quite near to that of a human arm, even though the human shoulder has more than two DOF. The analogy between the human arm and the PUMA manipulator is true only from a kinematic point of view, because the two systems have completely different performances. We can assert that this robot is more precise than a human arm, nevertheless the natural arm is structurally conformed to perform tasks that require compliant features, like clean an irregular surface or catch a ball.

A fine regulation of the joint stiffness is therefore very important also in a Humanoid Robot, indeed if we want that the robot will be able to perform a task in collaboration with a human being we have the necessity to change the joints stiffness in concomitance with the robot movements. In industrial manipulators it is possible to set the end-effector compliance using the information coming from a three axis force sensor

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installed on the wrist, nevertheless this is quite similar to a virtual compliance control. In fact, the motors that equip the manipulator do not present an intrinsical compliance, normally if the power is switch off the robot assumes its maximum rigidity. This behavior is not acceptable for a robot that is thought to operate in strict contact with a human being.

With this work we want to propose a different methodology in developing such a systems, not only we tried to emulate the human arm morphology, but we implemented also a neural controller that replicates the functionalities of primary motor circuits located in the human spinal cord. We are convinced that combining classical control methodologies with bio-inspired one may brings a new class of machines that will perform better.

There are many projects that attempted to design an arm with human like features and capabilities. At the Center for Intelligent Systems (Vanderbilt University) Prof. Kawamura and its group are working on the ISAC humanoid robot. This robot consists of a human-like trunk equipped with two six-DOF arms moved by McKibben artificial muscles (Kawamura et al., 2000). Each joint is actuated by two antagonistic actuators that are controlled by a system able to emulate the electromyogram patterns (EMG) of a human muscle. The arm, during a fast reaching movement, can avoid an obstacle performing a reflex behavior (Gamal et al., 1992), furthermore the phasic pattern is autonomously adjusted when a reach trajectory doesn't closely match a desired response. The main advantage of this bio-mimetic control architecture is the possibility to reduce the joint stiffness during a movement execution.
Another project in the same direction is that one at the Biorobotics Laboratory in Washington University. Here Prof. Hannaford and his team have worked intensely on the emulation of the human arm (Hannaford and Chou, 1997) (Hannaford et al., 1995). The goal of this research is to transfer knowledge from human neuro-musculo-skeletal motion control to robotics in order to design an "anthroform" robotic arm system.

Following the bio-mimetic approach they developed and tested new kind of actuators (Klute and Hannaford, 2000) and sensors (Hannaford et al., 2001) (Jaax, 2001), whose purpose is to replicate a mammalian muscle spindle cell, that measures the contraction and the muscle velocity.

Another very interesting arm project is that one developed by Department of Precision Machinery Engineering in University of Tokyo. The system(Toshiki Niino and Higuchi, 1994) is equipped with a new types of compact, high-power, electrostatically driven actuators.

The actuators have 40 or 50 pairs of sheets interleaved together and enclosed in ready-to-use packages filled with a dielectric liquid. An electrostatic artificial muscle consists of two groups of sheets stacked and interleaved together. Sliding forces are generated on the surface of each film and are combined into a net force at the bundled edges of the sheets.

A first type of pulse-drive induction artificial muscle, which utilizes induced charges on highly resistive films, generated 8N propulsive force and 0.5W mechanical power with 110g its own mass. At the Dept. of Mechanical Engineering (Vrije Universiteit Brussel) Prof. Frank Daerden et al designed a new type of Pneumatic Artificial Muscle (PMA), namely the Pleated Pneumatic Artificial Muscle (PPAM) (Daerden and Lefeber, 2001). It was developed as an improvement with regard to existing types of PAM, e.g. the McKibben muscle (Klute and Hannaford, 2000).

Its principal characteristic is its pleated membrane. It can inflate without material stretching and friction and has practically no stress in the direction perpendicular to its axis of symmetry. Besides these it is extremely strong and yet very lightweight and it has a large stroke compared to other designs.

2 THE ARM ARCHITECTURE AND FEATURES

In 2003 we developed a first prototype of artificial Arm (MaximumOne Figure 1) with the main aim to experience the actuation architecture and the control strategies we theorized.

From the kinematic point of view, if we exclude the hand, the system presents overall four degrees of freedom. Three are located in the shoulder that resembles a spherical joint, and one in the elbow that is a normal revolution joint.

Each joint is actuated by tendons connected with McKibben artificial muscles. In order to detect the arm posture and allow to close the control loop, each actuator is equipped with a position and force sensor. These devices were developed specifically for this application, this because there are not commercial system that meet our needs. Furthermore the elbow joint is furnished of an angular sensor (Figure 1) that measures the joint position.

The signals coming from the sensors are conditioned and gathered by dedicated boards that perform an analog multiplexing and send the information to a **Target-PC** equipped with a real-time kernel. The control system, implemented via software on a **Host-PC**, receives and elaborates these information via RS-232 serial connection and send 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 14 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.

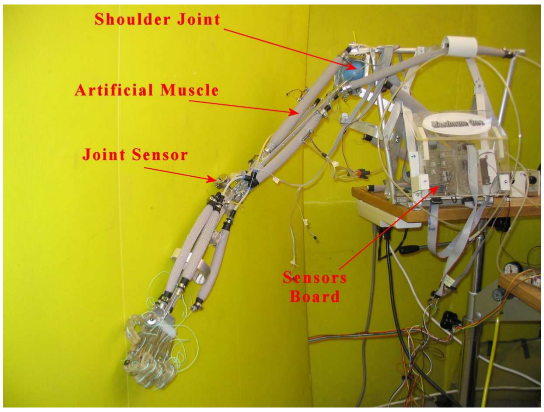


Figure 1: MaximumOne,the Arm Prototype of the Artificial Intelligence and Robotics Laboratory, Politecnico di Milano.

As it is possible to see from the picture (Figure 1), the arm we developed has an anthropomorphic shape. This because during the design, we have tried to reproduce the human arm dimensions and proportions, the articulation mobilities, the muscle structure, and the same sensorial capabilities.

2.1 The Actuation System

In order to actuate the arm we used seven artificial muscles (Figure 2): five are dedicated to the shoulder joint and two to actuate the elbow. This permits us to obtain the typical postures and movements of the natural limb. The five shoulder actuators emulate the mechanical functionalities of: pectoralis major, dorsal major, deltoid, supraspinatus and subscapularis muscles. The two elbow actuators emulate the functions of biceps and triceps muscles.

If we compare the the human arm musculature with the actuation system of our prototype we can find out same differences; for example the actuators that represent the biceps and triceps muscles are monolink in the sense that they are dedicated only for the elbow actuation, instead in the human limb they interest at the same time the shoulder and elbow articulations. Furthermore shoulder actuators are placed

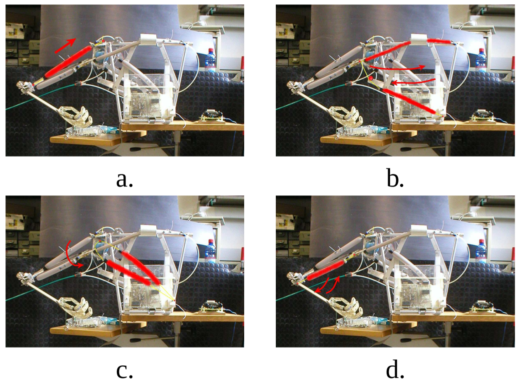


Figure 2: (a) The Deltoid Actuator lifts the shoulder. (b)The Pectoral and Dorsal Actuators allow the adduction and abduction movements. (C)The Supraspinatus and Subscapularis Actuators allow the shoulder rotation. (d) The Biceps and Triceps Actuators allow the elbow flexion and extension.

in a manner to maximize the space available for their movement. Indeed, because of McKibben actuators can contract only the 20% of their maximum length, depending on the tendon excursion we need to realize, their minimum length is fixed.

3 CONFIGURATION OF THE CONTROL SYSTEM

The control system of the arm is organized in a modular and hierarchical fashion. At the bottom level (Figure 3) there are the artificial reflex modules(Michele Folgheraiter, 2004) 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 the P signal that scales the level of artificial muscles co-activation (simultaneously activation of the muscle that govern the same joint).

From a hierarchical point of view, we can distinguish three main levels:

- **High level controller**: composed by the Inverse Kinematic modules
- **Medium level controller**: composed by the path generator module
- **Low level controller**: composed of the reflex modules that control the artificial muscles activities

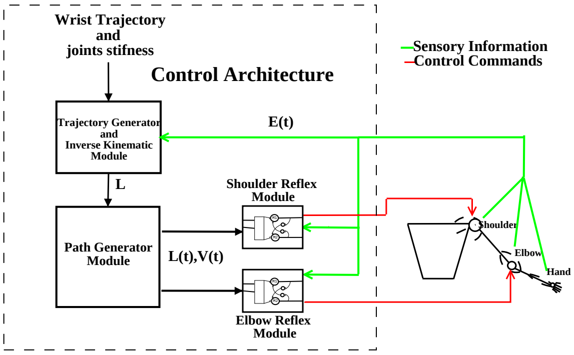


Figure 3: Control System Architecture.

The signals transmitted from one module to another are expressed in a vectorial form, where each vector component corresponds to one of the seven artificial muscles that compose the actuation system. Therefore L_T represents the target lengths vector for the actuators, V_T represents the target velocity vector, E_L represents the length vector error, and P is the stiffness command vector. At the level of each single module these signals are decomposed in their components and sent to the appropriate submodules.

4 ARTIFICIAL NEURAL CIRCUITS TO IMPLEMENT THE REFLEXES BEHAVIORS

Reflex behaviors are accomplished by two modules that implement a simplified model of the natural circuits present in the human spinal cord. One module is dedicated to the control of the artificial muscles activities that govern the shoulder joint, the other takes under control muscles that actuate the elbow joint. Since the artificial muscle is constituted by only one functional fiber the biological organization of the natural muscle in motor units is neglected in our model. The artificial muscle activity is therefore regulated by only one 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.

The most important cells of the neural circuit are the motoneurons whose outputs set the actuators pressures. With respect to other models in literature (Sterratt, 2001),(Kuntimad and Ranganath, 1999),(Folgheraiter and Gini, 2001) or to hardware solutions (Omura, 1999) we decided to neglect the spike behavior of these cells, instead we concentrated our attention on modelling its membrane potential.

Each motoneuron receives its inputs from almost all the cells that compose the circuit. In equation 1 M_i represents the potential (membrane potential) of the motoneuron **i**.

$$\frac{d}{dt}M_i = (1 - M_i)(exc_i) - M_i(inh_i) \qquad (1)$$

where the terms exc_i and inh_i are the excitatory and inhibitory inputs for the motoneuron.

The neuron output is represented by equation 2

$$Mo_i = Th(M_i) \qquad (2)$$

where the threshold function is defined by equations 3 :

$$Th(x) = \begin{cases} x & \text{if } 0 \leq x \leq 1 \\ 0 & \text{if } x \leq 0 \\ 1 & \text{if } x \geq 1 \end{cases} \qquad (3)$$

For more details about this model see (blind).

4.1 Elbow Neural Circuit

The reflex module that governs the elbow muscle is represented in figure 4. It implements an opponent force controller whose purposes are to provide inputs for the path generator module, measure movements error and return error signals when the execution is different from the desired movement.

In figure 4 M_6 and M_7 are the motoneurons that control the contraction rate and force of the triceps and biceps actuators respectively. I_a6 and I_a7 are the interneurons that receive the error signals from the artificial spindles and project, with inhibitory synapses, to the motoneurons of the antagonist muscles M_7 and M_6 respectively. R_6 and R_7 represent the Renshaw cells that receive the error signals from spindles and inhibit the corresponding motoneuron and I_a cell, they are important to reduce oscillations of the joint around the target angular position. I_b6 and I_b7 are interneurons that receive the signals coming from the artificial Golgi tendon organs (that in this system are represented by a normalized force measurements). $I_{ns}6$ and $I_{ns}7$ are the interneurons that integrate information of stiffness and target length commands.

Finally M_s6 and M_s7 represent the artificial muscle spindle receptors. As inputs they receive the muscle velocity command, the muscle target length command and the actual muscle length and in turn excite the corresponding motoneuron and I_a interneurons.

In this work we do not consider the other inputs (show in the neural circuit schema) for more details see (Folgheraiter, 2003).

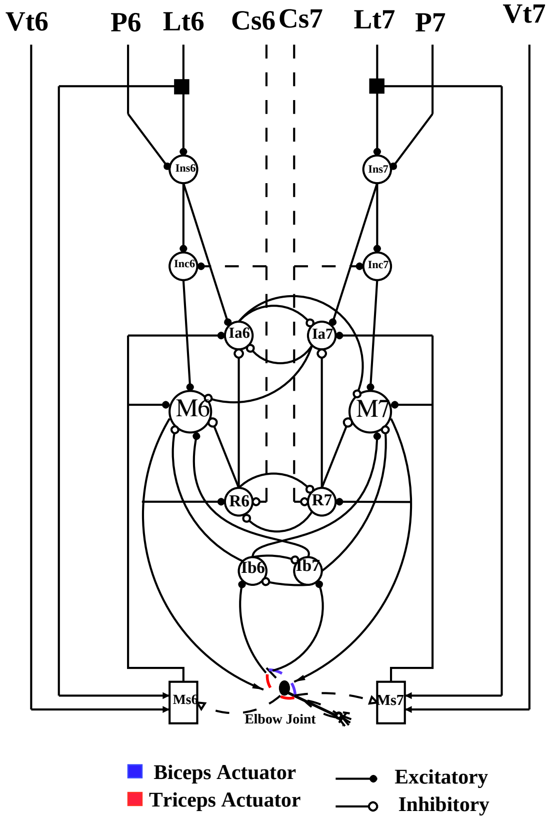


Figure 4: Architecture of the Elbow Reflex Module.

5 TRAJECTORY GENERATION: DIRECT AND INVERSE KINEMATIC

In order to test the efficacy of the control system we developed two kind of arm models:

- **The Kinematic Model**: it is used in the inverse kinematic algorithm to calculate the distance between the target position and the actual position for the wrist.
- **The Dynamic Model**: it represents a realistic model of the arm and takes into account the dynamic features of the actuators and of the arm links.

In this paper we will briefly describe only the Direct Kinematic model, because of it is required to develops the Arm Inverse Kinematic algorithm.

6 DIRECT KINEMATICS

Find the Direct Kinematics of the arm means to find the function that relates the actuator lengths vector with the wrist position. In this case the orientation is not considered because, if we do not take into account the hand, the kinematic chain, with only four DOF (three in the shoulder and one in the elbow), does not allows to set arbitrarily both the position and orientation of the wrist. It is possible to find the Direct Kinematic of the arm solving a system of equations, where each one imposes a constraint on the arm position. As an example, if we consider the pectoral and dorsal actuators we can obtains equation 4.

$$\begin{cases} (x-Opc_x)^2+(y-Opc_y)^2+(z-Opc_z)^2-Lpc^2=0 \\ (x-Odo_x)^2+(y-Odo_y)^2+(z-Odo_z)^2-Ldo^2=0 \\ (x-S_x)^2+(y-S_y)^2+(z-S_z)^2-(\|S-Opc\|)^2=0 \end{cases} \tag{4}$$

In equation (Eq. 4) (x,y,z) is the position where the two actuators are connected to the upper-arm, Opc and Odo represent the origins of the pectoralis and dorsal respectively, Lpc and Ldo are the actuator lengths, and S is the shoulder position. All the quantities are referred to the Arm reference system. The first two equations impose that the distance between the two extremities of the artificial muscle are equal to the required distance, instead the third equation imposes the condition that at the end of the movement the position of the attachment of the artificial muscles compared to the bone doesn't result modified. As it is possible to see equation 4 has two solutions and should be recalculated every time the position of the upper arm changes, indeed it depends on (x,y,z) a point located on the first robot link.

7 INVERSE KINEMATICS

Inverse Kinematics allows the calculation of the muscles lengths vectors when a target position in the robot workspace is assigned.

The algorithm we implemented for the Inverse Kinematics is based on the gradient descent method, this in order to calculate the minimum of the distance function between the current and the target wrist position. It approaches a local minimum by taking steps that are proportional to the negative of the gradient. We can codify the algorithm using the pseudo-code of figure 5.

Where ε_{max} is the maximum error allowed in reaching the target position, and subsets $Sub(i)$ represents a couple of actuators chosen with a specific

```
- Set Current Wrist Position
- Set Target Wrist Position
- Calculate Distance between Current Position and  Target Position

while ( Distance > ε_max)
   for i=1:4
        for each muscle belonging Sub(i)
                - Decrease its length
                - Calculate the effect on the end-effector position ( Direct Kinematic)
                - Calculate the Distance between Current Position and Target Position
                if (Distance decreases)
                   - Calculate the step size
                   - Update muscle length
                end
        end
   end
end
```

Figure 5: The Algorithm that implement the Arm Inverse Kinematics. .

logic from the set of all arm actuators.

As it is possible to see the actuator length is decreased of a value D specified by equation 5 only if its decreasing allows to approach the target position, if not its antagonist actuator is considered at the next step.

$$D = -\frac{1 - e^{\frac{-(TargetP - WrisP)}{K_1}}}{K_2} \quad (5)$$

As it is possible to see from equation 5 depending from the two constant K_1 and K_2 the muscle length variation decreases according to the decreasing of the distance between the wrist position ($WristP$) and the target position (TargetP).

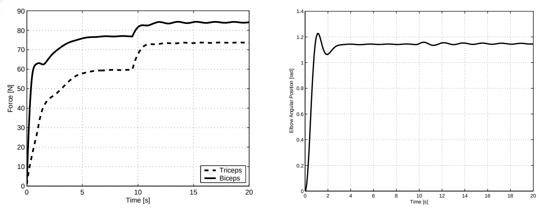
At each cycle the Direct Kinematic should be calculated and this requires a certain amount of time, in simulation this does not represent a problem, but may be critical during the normal arm operation. Nevertheless we can avoid to calculate the direct kinematics installing on the robot a vision system that can approximate the distance between the wrist and the target position. This strategy is very similar to that one performed by humans when it is required to perform a motor path in order to reach a target object. At least during the learning phase, humans being take advantage of the visual feedback to estimate the distance between the object and the hand.

8 STIFFNESS CONTROL AND TRAJECTORY FOLLOWING

Here we report the results of some simulations conducted on the robot models. The dynamic model was developed using the tool SimMechanics in Simulink environment, we chose an integration step of 1ms in order to comply with the arm dynamic. At first we tested the ability of the neural circuit in regulating the elbow stiffness, in this case a noise force was applied on the wrist. In the second part of our experiments we tested the performance of the controller in following an assigned trajectory, changing the precision we show that the algorithm time complexity will decrease exponentially.

8.1 Joint Stiffness Regulation

The control of the joint's stiffness is very important during the execution of a certain task with the robot's arm. This is true for industrial robots, but is particulary important for humanoid robots. Usually industrial manipulators operate in a protected environment where humans have a restricted access, in order to guarantee a safe operation for the robot and for the human. It is difficult to control the joint stiffness for an industrial manipulator and even if this is possible the inertia force that acts during the movement can be lethal for a human being hit by the robot. Humanoid robots are expected to operate and collaborate with humans, during a task execution, therefore the robot must not be dangerous; 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 a stiffness increase of the lower and upper body articulations, while making a caress to someone requires a low stiffness for the arm's articulations. The articulation's stiffness, in turn, is regulated by the muscle cocontraction.
In the reflex modules the stiffness is regulated by the P_i signals that excite the Ins interneurons. In order to demonstrate such a capability in the reflex module I increased the P_i signals for the elbow actuators to the maximum value possible, 1. Picture 6a shows the forces increasing due to the P command.



a. b.

Figure 6: (a) Biceps and Triceps forces during the application of a dangerous force to the hand. (b) Elbow angular position during the increasing of the joint's stiffness.

The forces in the biceps and triceps actuators increase at the same time, in order to avoid the joint movement. We can observe also that the triceps increases its force more than the biceps; the important thing is that the total momentum exercised on the elbow joint is equal to zero in order to guarantee its position (Figure 6b). As it is possible to note, the elbow position does not change when its stiffness is increased. We can also observe a collateral effect due to the stiffness increasing: for a certain period there are some little oscillations in the elbow joint. Surprisingly this phenomena is present also in humans. When the muscles are very highly co-contracted, a tremor will occur in the arm.

8.2 Trajectory Following

In the first simulation (Figure 7) the arm follows a straight trajectory from the position (0.46,-14) to the position (0.46,9), all the quantities are expressed relatively to the robot workspace. In this case we impose a maximum deviation from the reference trajectory of 6mm, the average error is 5mm. We can increase the precision, but this will also increase exponentially the computational time require to calculate the trajectory.

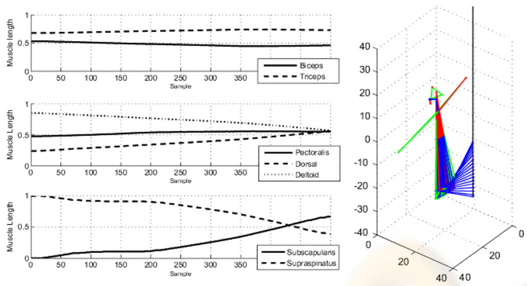


Figure 7: Following a straight trajectory.

In figure 7 are showed also the normalized values for the actuators lengths, as it is possible to note the biceps and triceps actuators lengths do not change considerably. There is instead a big upper arm rotation (relative to an axis which direction is equal to the first link direction), due to a big variation of the supraspinatus and subscapularis actuators lengths.

In the second simulation (8) we give as reference a more complex trajectory (useful for example to avoid an obstacle in the workspace), also in this case the trajectory is well followed by the wrist.

Finally figure 9 shows the trend for the computational time complexity relative to the precision in reaching the target position. As it is possible to see the trend is exponential, this means that the chose of the robot precision is a critical factor for the control system.

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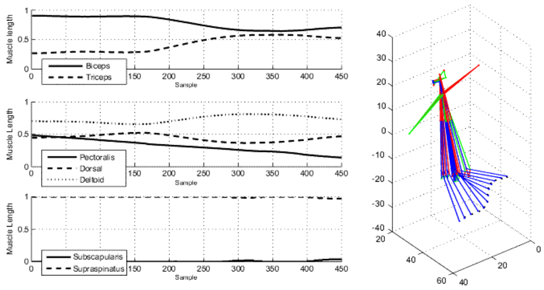

Figure 8: Following a complex trajectory.

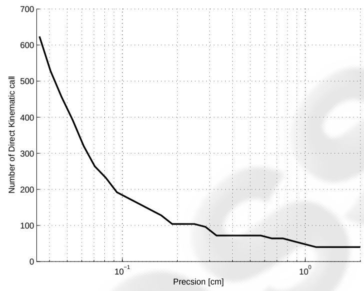

Figure 9: Trend for the time complexity.

9 CONCLUSION AND FUTURE DEVELOPMENTS

In this paper we describe the architecture and the main features of an anthropomorphic artificial arm intended for applications in the field of the Humanoid Robotics. In particular we analyzed its actuation system, that emulates the arrangement of the human musculature, and its 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, this 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 to regulate, during the movement execution, the joint stiffness. This is very important especially for the execution of specific tasks in collaboration with human beings. Future works will require to test the control system on the real arm and to compare the experimental results with the simulations conducted on the arm models.

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