MaximumOne: an Anthropomorphic Arm with Bio-Inspired Control System.

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Abstract. In this paper we present our bio-mimetic artificial arm and the simulation results on its low level control system. In accordance with the general view of the Biorobotics field we try to replicate the structure and the functionalities of the natural limb. The control system is organized in a hierarchical way, the low level control reproduces the human spinal reflexes and the high level the circuits present in the cerebral motor cortex and the cerebellum. Simulation show how the system can control the single joint position reducing the stiffness during the movement.

1 Introduction

The goal of this study was to develop an Artificial Arm that mimics the morphology and the functionality of a human limb. The approach that we have adopted is in accordance with the general view of the Biorobotics field.

People involved in this robotics branch ,[1],[2],[3],[4],[5],[6] believe that studying and mimicking a biological organism allows us to synthesize a robot with more powerful characteristics and functionalities than a classical robot, as well as to better understand the organism itself. Indeed, if we think of the history of technology, often humans were inspired by nature. Famous are the studies conducted by Leonardo da Vinci between 1487 and 1497 on the flying machines, that were inspired by the birds. This does not mean that observing and studying nature we can find out the best solution for a specific problem. In fact, for example, our technology can synthesize flying machines that are much faster than any biological organism.

2 The ARM Prototype

The arm we built in our laboratory (Figure 1), is intended to be the natural test-bed for testing the control system architecture proposed in this work and for developing new technologies applicable to humanoid robotics. The arm, without considering the wrist and hand that are still under development, has two joints for a total of four degrees of freedom. The shoulder consists in a spherical joint with 3 DOF, and the elbow is a rotational joint with 1 DOF. Joints are moved by tendons connected with McKibben artificial muscles, which in turn are bonded with the support structure and the upper arm. Each "muscle" is equipped with a force sensor mounted in series to the actuator (comparable, from a functional point of view, with the Golgi tendon organ in the human arm) and of a position sensor located in parallel to the external shell that covers the artificial muscle (comparable, from a functional point of view, with the muscle spindle in the human arm). The elbow joint has also an angular sensor (Figure 1)that measures the joint position and velocity with more precision. Sensor signals are conditioned and gathered by dedicated boards and sent to a PC A/D card. The control system runs in real time on a target PC, and its output are converted in appropriate signals that feed the actuation system.

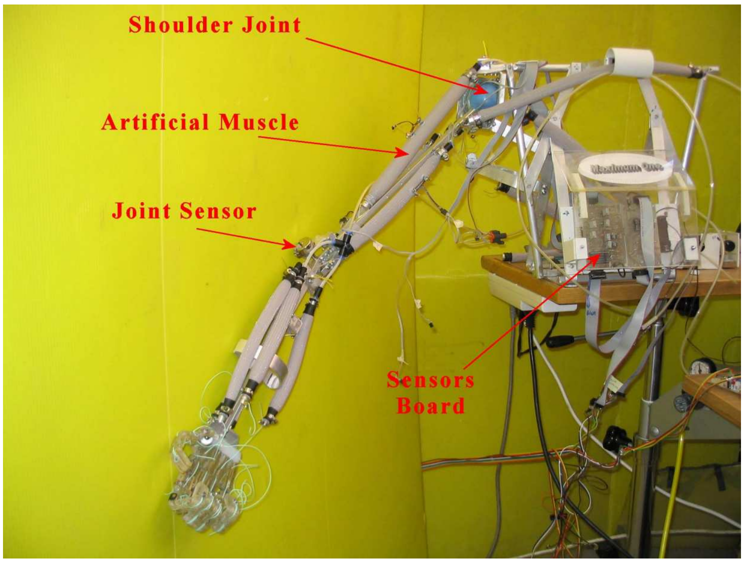

Fig. 1. The Arm Prototype, MaximumOne, Artificial Intelligence and Robotics Laboratory, Politecnico di Milano

As it is possible to see in the prototype picture (Figure 1), this arm has an anthropomorphic design. In particular, 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. The actuation system is composed of seven muscles: five actuate the shoulder joint and two the elbow. This permits us to fully actuate the joints but at the same time to have a minimal architecture. The five shoulder actuators emulate the function of: pectoralis major, dorsal major, deltoid, supraspinatus and subscapularis muscles. The two elbow actuators emulate the function of biceps and triceps muscles. In comparison with the human arm musculature, the actuation system of our prototype is quite different, for example the biceps and triceps artificial muscles are mono-articular in the sense that they are dedicated only for the elbow actuation.

3 Architecture of the Control System

The control system of the arm is organized in a modular and hierarchical fashion. At the bottom level (Figure 2) 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 reflex modules also receive inputs from the cerebellar module whose function is to regulate the path generator outputs. The cerebellum module, as inputs, receives signals from the path generator modules and the error signals from the reflex modules. The inputs of the entire control system are: the final hand position in the cartesian space, the GO signal that scale the speed of movement and the P signal that scales the level of artificial muscles co-activation (simultaneously activation of the muscle that govern the same joint).

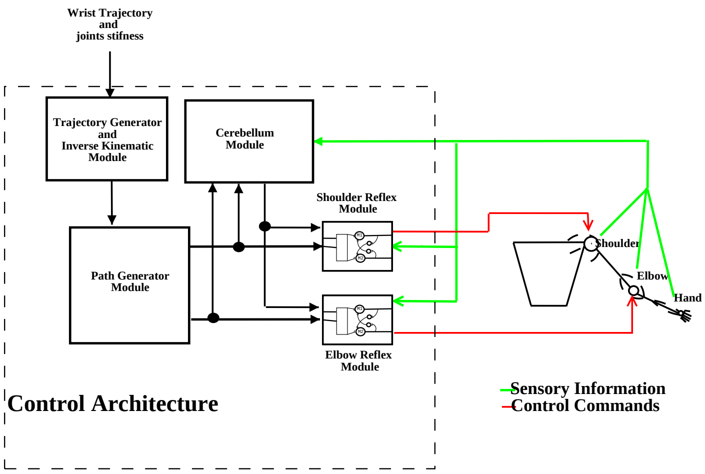

Fig. 2. Control System Architecture

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

High level controller :composed of the Inverse Kinematic and the cerebellum modules that cooperate in parallel to control the path generator activity

Medium level controller :composed of the path generator module. This is capable of generating desired arm movement trajectories by smoothly interpolating between the initial and the final length commands for the synergetic muscles that contribute to a multi-joint movement.

Low level controller :composed of the reflex modules that control the artificial muscles activities

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 for the actuators, E_L represents the length vector error of the actuators, C_S is the signal vector generated by the cerebellum module, 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.
In this paper, for brevity, we do not deal with the Inverse kinematic, the cerebellum and the Path Generator modules, but we will concentrate our attention only on the Reflex module.

3.1 Joint Reflex Control Module

Reflex behaviors are accomplished by modules that implement a simplified model of the natural circuits present in the human spinal cord. With respect to other models in literature [7],[8],[9],[10], or to hardware solutions [11]we decided to neglect the spike behavior of the neuron for all the artificial cells, instead we concentrated our attention on modelling its membrane potential. From an information point of view the spiking behavior in the neuron is not so crucial. In a living organism the action potential mechanism permits to convert an information, represented by the neuron potential (analog signal), into an impulsive signals. In such a manner the information is transmitted modulating the frequency of the impulsive signal. This is particulary useful when the signal (of few mV) is transmitted over a long distance, for example from the arm receptors (peripheral nervous system) to the central nervous system. In our system (arm prototype) the entity of the sensor signals are in the order of some volts, and all the information are processed in a normal CPU, so it is not efficient convert the analog signals into a impulsive signals.

The reflex module that governs the elbow muscle is represented in figure 3. It implements an opponent force controller whose purposes are to attempt to implement the path generator module commands, measure movements error and return error signals when the execution is different from the desired movement. In figure 3 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). $I_{nc}6$ and $I_{nc}7$ are interneurons whose purpose is to integrate information coming from the cerebellum (signals C_s6 and C_s7) and from the $I_{ns}6$ and $I_{ns}7$ interneurons, thanks to these cells the cerebellum module can apply its influence on the overall joint movement. $I_{ns}6$ 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.

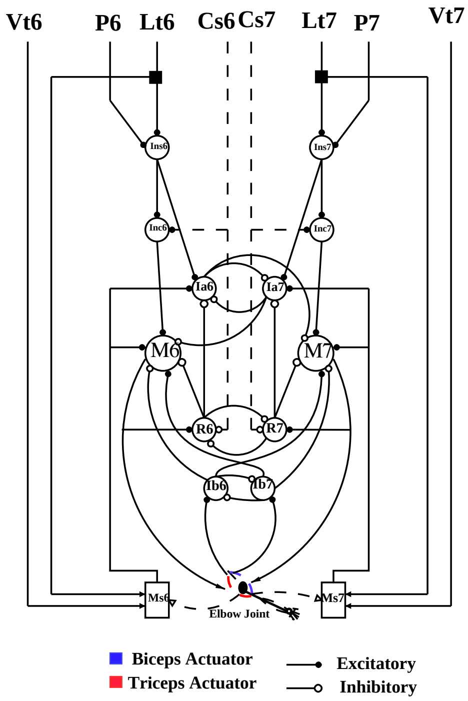

Fig. 3. Architecture of the Elbow Reflex Module

Neurons Model Each artificial neuron is described by a not linear differential equation. Neurons models differ only for the constant values and the inputs, therefore here we will describe only the motoneuron equations.

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

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

where the terms exc_i and inh_i are expressed by equations 2

$$
\begin{array}{l}
exc_i = w_1 \cdot E_i + w_2 \cdot Inc_i + \sum_{k=1,k\neq i}^{n}(z_k \cdot Ib_k) \\
inh_i = K + w_3 \cdot R_i + w_4 \cdot Ib_i + \sum_{k=1,k\neq i}^{n}(v_k \cdot Ia_i)
\end{array} \tag{2}
$$

the motoneuron output is

$$Mo_i = Th(M_i) \tag{3}$$

where the threshold function is defined by equations 4 :

$$Th(x) = \begin{cases} x & \text{if } 0 \leq x \leq 1 \\ 0 & \text{if } x \leq 0 \\ 1 & \text{if } x \geq 1 \end{cases} \tag{4}$$

The first term in the right side of the equation 1 is the gain for the excitatory part (**exc**); this gain is a function of the motoneuron potential. Therefore, the more the neuron is actives the smaller the gain will became. This avoids the neuron's potential saturating rapidly when the excitatory synapses are strongly stimulated. The second part of the equation 1 gathers the inhibitory signals that feed the motoneuron (**inh**). In the (**inh**) term the inhibitory signals are multiplied by the corresponding synapse's gain w_i and v_k, and added together. It is clear, that the gain for the excitatory part 1will decrease when the motoneuron potential increases. This contributes to maintain the neuron activation confined under the maximum value. The summation in the (**inh**) part, takes in account of the inhibitory action of the antagonistic Ia_i, the summation is extended to **n**, the number of motoneurons that constitute the reflex circuit (n=2 for the elbow reflex circuit and 3 for the shoulder reflex circuit).
The term K represents the leaky current of the neuron membrane. When the neuron is not excited its potential will decrease thank to this term. Finally E_i is the error signal coming from the spindle cell Ms_i.

4 Test on the Reflex Module

The first simulation shows how the elbow reflex module can govern the actuator pressures in order to regulate the joint position. In this simulation the biceps and triceps length commands were manually set, therefore the path generator module, and the inverse kinematic module are not yet connected to the reflex circuit. In figure 4 the elbow angular position during the entire motion is reported.

We see that the elbow position in the first movement reaches 0.4 radians (24.2^o), with the second movement that starts at the fifth second it reaches 1.15 radians (70^o), and finally the joint is restored to the first position.

Note that in the first movement there is a big over-elongation, partially due to the fact that when the first movement starts all the neurons potentials are set at the minimum value, and it take a certain time for the neurons to reach the operative value. In the arm prototype a minimum motoneuron activity is needed in order to maintain a sufficient pressure inside the artificial muscles. This to

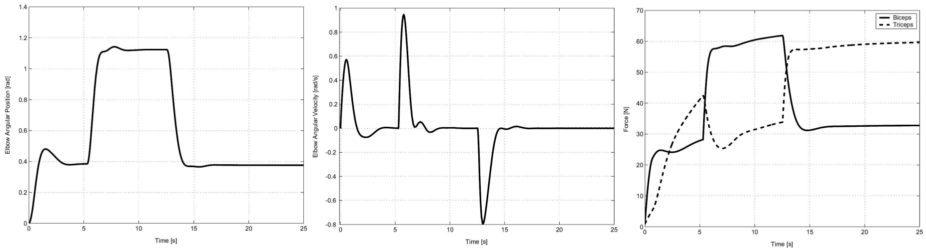

Fig. 4. The Angular position and velocity of the Elbow (two first graphs). The biceps and triceps forces (last graph)

avoid the detachment of the inner tube from the external braided shell.
It is possible to note from the graph, that also in the second joint movement there is a certain over-elongation, but this is reduced in comparison with the first one.

From figure 4 it is possible to see how the elbow's velocity follows a human bell shape profile, thanks to the smooth control behavior of the motoneurons. In figure 5 are reported the motoneuron and interneuron signals during the elbow flexion.

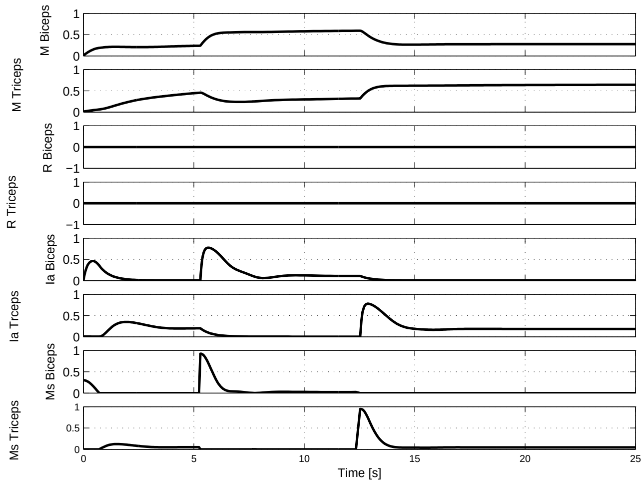

Fig. 5. Motoneuron and interneurons activities during the Elbow flexion

Starting from the bottom we can see the activities of the artificial spindles Ms_i that measure the length and velocity errors in the biceps and triceps actuators. When the first elbow movement starts, the biceps's spindle increases its activity rapidly this because, in comparison with the length command, the actuator should be shorter. After 0.8 seconds the biceps's Ms decreases its activity to zero , but at the same time there is a burst in the triceps's Ms, due to the fact that the elbow has overcame the target position and therefore the triceps should be contracted. Looking at the axes that report the Ia interneuron outputs, it is possible to note that the activity of this neuron are strictly correlated with those of the Ms. Nevertheless their effect, now, is transmitted on the antagonistic motoneuron. This action is very important for the elbow joint control. Indeed thanks to this cross inhibition a big length or velocity error on an artificial muscle, not only increases its pressure, but decreases at the same time the pressure in the antagonistic artificial muscle. We can see this influence in the motoneurons activities or directly on the actuator force.

In this first simulation I prevented the action of the R_i (Renshaw cells) interneurons, as it is possible to see in the graph of figure 5. They are important to maintain the motoneuron activity under control when the elbow has reached a stable position. From the graph that depicts the actuator force (last graph of figure 4) it is possible to note that when each movement is ended the force increases autonomously in both the motoneurons, this causes a stiffness increasing in the elbow joint. In humans this disease is called hypertonia.
In the following simulation I enabled the R_i interneurons and performed the same movements as the first experiment (Figure 6).

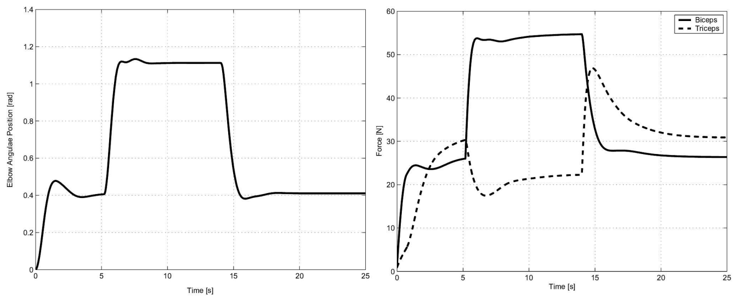

Fig. 6. The Angular position and the forces generated by the Biceps and Triceps actuators of the Elbow in the second experiment

This time, even thought the elbow performed the same movements, the actuators force changed. Indeed from the second graph of 6 it is possible to note that after each movement the forces don't increase like in the first experiment. This behavior is due to the R_i interneurons that limit the motoneurons potential when the elbow doesn't move.

5 Conclusion

The main aim of this work was the development of a human-like artificial arm for application in the field of humanoid robotics. Because mimicking the human arm from the mechanical and functional point of view was one of our principal research aims, we conducted an intensive study of the natural limb. We concentrated our attention to the design and the implementation of a real human-like robotic arm, and at the same time, to developing a possible control model based on the actual knowledge that neurophysiologists have of the human nervous system.

Our arm differs from other analogous systems [12], [3], [13], by the presence of a full 3DOF shoulder joint moved by five artificial muscles. Furthermore, thanks to the employment of light materials, the system can be integrated with a whole humanoid robot. Results, on the low level control system, show how it can set the single joint position and stiffness in a efficiently way.

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