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Bio-Inspired Controller for a Dexterous Prosthetic Hand Based on Principal Components Analysis

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Abstract—**Controlling a dexterous myoelectric prosthetic hand with many degrees of freedom (DoFs) could be a very demanding task, which requires the amputee for high concentration and ability in modulating many different muscular contraction signals. In this work a new approach to multi-DoF control is proposed, which makes use of Principal Component Analysis (PCA) to reduce the DoFs space dimensionality and allow to drive a 15 DoFs hand by means of a 2 DoFs signal. This approach has been tested and properly adapted to work onto the underactuated robotic hand named CyberHand, using mouse cursor coordinates as input signals and a principal components (PCs) matrix taken from the literature. First trials show the feasibility of performing grasps using this method. Further tests with real EMG signals are foreseen.**

I. INTRODUCTION

The design and development of a prosthetic artificial hand should aim as much as possible at replacing both functionality and cosmetic appearance of the natural hand lost by the amputee. Surveys on using commercial prosthetic hands reveal that 30 to 50% of upper extremity amputees do not use their prosthetic hand regularly [1]. The main factors for this are low functionality and controllability, poor cosmetic appearance and an unnatural control system [2], which make the hand to be felt as an external device that is not part of the subject's body scheme.

Analyzing the actual state of the art, researchers have developed several experimental, articulated robotic hand prototypes able to correctly mimic human movements; Bicchi gives an exhaustive summary of the results achieved in this field [3]. Nowadays, the real problem stands no more in these limbs mechatronic design as in the controllability of such complex systems: the lack of a control interface especially designed to drive many DoFs during daily living activities makes them not suitable in prosthetics. Because of these drawbacks, commercial prostheses, like OttoBock (Germany), Motion Control (Utah) and Liberating Technologies (Massachusetts), even if purposely designed to be reliable, robust, simple to use and cosmetically acceptable, have just one (or two) DoFs. Such feature combined to their rigid actuation scheme, leads to the implementation of only some basic functionalities [2]. It is clear that devices available on the market are something very similar to rough grippers able to generate the required grasping forces but with a drastically reduced number of DoFs and dexterity.

The human hand instead is a very complex system, both from a biomechanical point of view and for what concerns control strategies: as a matter of fact, a lot of synergic muscular and neurosensory mechanisms are involved to achieve high dexterity. Correctly driving a multi-DoF prosthetic hand to perform a variety of natural prehensile patterns, implies controlling at high speed each of its DoFs separately. Therefore, if we think of an amputee trying to use an EMG-controlled prosthesis, the learning process required to selectively modulate many different contraction signals in order to make each joint move independently could be almost impossible indeed. Thus, the real challenge, when developing a functional myoelectric prosthetic hand, is to design a friendly control system which does not need a high level of concentration and an excessive effort of the user, since a successful prosthetization depends mostly on whether the patient learns to integrate it into his/her own body scheme or not. All this by providing the artificial limb with high dexterity and functionality at the same time.

This problem has already been partially addressed by underactuated hands, as the CyberHand prototype [4]. Such an approach allows performing most grasping behaviors of the human hand without increasing the complexity of the control [5].

In this paper we introduce some results obtained by combining an original control method based on Principal Component Analysis (PCA) [6] with the functioning mechanism of the previously mentioned CyberHand. Our aim is to reduce the complexity of a high number of DoFs device control system both algorithmically, by decreasing the number of signals involved in the control exploiting neuroscience literature results, and mechanically, employing an underactuated mechanism. Actually we think this could be a good alternative to the use of complicated EMG processing algorithms. The control system here proposed could be employed to drive commercial multi-DoF prostheses recently introduced in the market as the iLimb (Touch EMAS Inc.,

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Edinburgh, UK), which is still controlled as traditional prostheses are, i.e. all fingers open and close together.

II. MATERIALS AND METHODS

A. Rationale

Since developing a bio-mimetic prosthetic hand consists in replicating the human one in its fundamental structure and essential functions, the design process should consider the needs of the prosthesis users. This means that the efforts should be devoted to obtaining a device as similar as possible to the lost limb, both from an anatomical and biomechanical point of view and also for what concerns grasping capabilities, kinematic and dynamic performance. At the same time, the control system should exhibit a simple and natural management by the patient.

Referring to a myoelectric prosthetic hand, in the following sections we introduce the approach we used to address these problems. First of all, in section II.B the structure of the robotic hand is briefly described; then, in section II.C and D we present the proposed method to simplify the hand movement control algorithm and then tested just onto the CyberHand.

B. The CyberHand

The CyberHand [4], developed by ARTS Lab, Scuola Superiore Sant'Anna, Italy, can be defined as a stand-alone prosthetic-hand open platform. It is composed of five underactuated anthropomorphic fingers based on Hirose's soft finger mechanism [5], which are actuated by six DC motors. Five of them are employed for the flexion/extension of the fingers and a further one drives the thumb opposition and is housed inside the palm [7]. Since each finger is composed of three phalanxes the mechanical architecture presents 16 DoFs actuated by 6 Degrees of Motion (DoM).

In the underactuated finger the flexion is obtained by using a single DC motor which drives a tendon running along the phalanxes, wrapped around idle pulleys placed inside the joints (metacarpophalangeal, MCP; proximal-interphalangeal, PIP; distal-interphalangeal, DIP), while extension is obtained by means of torsion springs. Motion is transmitted from the motor to a lead screw acting as a slider which pulls the tendon. Thanks to the underactuated mechanism, when the hand closes it is able to wrap over objects, thus obtaining grasps with a high number of contact points. Nevertheless underactuation doesn't allow an independent control of each phalanx, and the final fingers (and whole hand) configuration is determined by the external constraints imposed by the shape of the grasped object.

The low level control architecture, responsible for grasping stability, relies on a sensory system which consists of five cable tension sensors, housed inside the sliders of each finger in series with the tendon stop and therefore giving information on the grip force, six incremental magnetic encoders integrated in the motors and a couple of Hall effect proximity sensors for each slider [8]. A proportional, integrative, derivative (PID) position control system is implemented by the embedded control system.

C. Prosthetic Control

A series of interesting experimental studies carried out by M. Santello and J. Soetching revealed that actually the control of the hand posture involves few postural synergies, coupled with a finer control mechanism [9].

They asked subjects to shape their right hand as if to grasp and use a large number of imagined objects; hand posture was measured by 15 sensors embedded into the CyberGlove (Virtual Technologies, Palo Alto, CA) [10], so that the angular positions of the 15 finger joints were acquired, thus accounting for 15 DoFs. Data analysis showed that not all the joint angles are controlled independently: observing patterns of covariation among them, it is intuitive to realize that some DoFs tend to be correlated with each other indeed [9]. Moreover, PCA was used to identify the effective number of DoFs: it was demonstrated that actually the first two PCs accounted for more than the 80% of the variance of motion, implying a significant reduction in the number of DoFs.

Underpinning on these assumptions, a sort of "inverse PCA algorithm" could be used to simplify the control problem. Since the EMG prosthetic control technology is mostly used and well developed in upper limb prosthetics, a new way of controlling multi-DoF prostheses was proposed [6], which provides for coupling two independent EMG signals with the two PCs, so that the system could be controlled as soon as the PCs map would be learnt by the subject. A virtual hand control model was introduced by the authors in a previous work [6], which implemented a driver capturing the 2 DoFs mouse signals as model inputs. Once the controller received the x y real-time coordinates of the cursor on the screen, it converted them into PC_1 and PC_2; finally, multiplying by the PCs matrix of [9], the 15 hand DoFs were returned and used to drive the virtual hand movement.

D. Controlling the CyberHand with Two PCs

Having to deal with an underactuated six DoMs hand, the PCs control algorithm can't be applied as it was to the virtual fully-actuated hand. The 15 joint angle values, each time obtained processing the instantaneous mouse x y position, must be reduced to six in order to drive the six CyberHand motors, thus it is important to find some relationships which combine each finger MCP, PIP and DIP angles in a single motor command value.

Several studies presented in the neuroscience literature [11] [12] assert that a proportionality exists between PIP and DIP angles (respectively, θ_{PIP} and θ_{DIP}) of the same finger, that is: $\theta_{DIP} = 2/3\ \theta_{PIP}$, while the same thing cannot be said for PIP and MCP angles (θ_{MCP}). Nevertheless, we must take into account the building structure of the robotic hand we are working on, with all the mechanical constraints inherent in its functioning mechanism.

Since the CyberHand fingers can be driven by a PID position control system using encoders, the set-point command values to be sent to each motor are proportional to their respective tendon cable shortening and consequently to their slider linear displacement (x_s). If we consider a singular finger, kinematics among the joints is related to the slider one [13] by this first approximation relation:

$$x_s = r_1\theta_{MCP} + r_2\theta_{PIP} + r_3\theta_{DIP} \quad (1)$$

where r_i, $i=1,2,3$, are the pulley radii (r_1 = 7 mm, r_2 = 3 mm, r_3 = 2 mm) and θ_{MCP}, θ_{PIP}, θ_{DIP} can vary from 0° to 90°. The dynamic relationship among joint torques (τ_1, τ_2, τ_3) and cable tension (T) is:

$$\tau_i = r_i T, \quad i = 1,2,3. \quad (2)$$

With reference to the PID control law in the joint space with elastic compensation [13], simplifying, we can write:

$$\tau_i = k_i\theta_i, \quad i = 1,2,3. \quad (3)$$

which represents the joint elastic torque term, where k_i is spring i stiffness coefficient and $\theta_1 = \theta_{MCP}$, $\theta_2 = \theta_{PIP}$, $\theta_3 = \theta_{DIP}$. Combining equations (2) and (3), we obtain:

$$\theta_{DIP} = \frac{k_2 r_3}{k_3 r_2}\theta_{PIP} \approx \frac{2}{3}\theta_{PIP},$$

which is the same result mentioned before, since all k coefficients are very similar and their ratio is almost 1. Thus, it is possible to rewrite relation (1) as:

$$x_s \approx 7\theta_{MCP} + 4.33\theta_{PIP}. \quad (A)$$

where both θ_{MCP} and θ_{PIP} are part of the 15 angle values resulting when processing the x y mouse coordinates (that is, multiplying PC_1, PC_2 by the PCs matrix, section II.C)

For what concerns thumb opposition instead, we can simply drive its motor with a value proportional to the thumb rotation angle resulting from the PCs algorithm.

The CyberHand can be directly controlled from an external device through a serial communication protocol (RS232), sending strings composed of a variable number of bytes to the controller. In such protocol, the position information is encoded using 8 bits. For this reason, the obtained x_s value must be in the end rescaled to vary into the range 0 (all joint angles = 0°: finger completely extended) – 255 (all joint angles = 90°: finger completely flexed) before sending the command to the robotic hand.

III. RESULTS

A C program was implemented to control the hand simply using two signals (the mouse cursor x y coordinates) thanks to the PCs algorithm introduced in section II.C and to the CyberHand communication protocol.

Every 10 milliseconds the program acquires the mouse cursor x and y coordinates in the monitor screen reference system; then it converts them into PC_1 and PC_2, scaling x and y values to make PC_1 vary in the range [-31; 31] and PC_2 in the range [-18; 18], since these are approximately the upper and lower bounds of the two first PCs as identified in [9]. All the remaining 13 PCs are set to zero, since the same study demonstrated that they have a very low weight, being thus negligible. Then the PCs vector is multiplied by the PCs matrix relative to one of the subjects' grasping trials analyzed in [9].

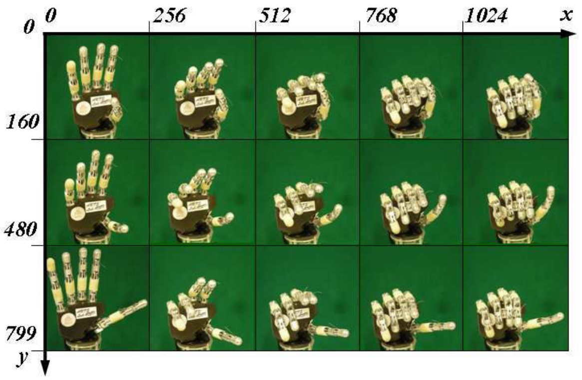

Fig. 1. Hand postures obtained moving the mouse in the monitor screen x y reference system.

The obtained 15 values are then used to calculate the six motors command values, varying in the range [0; 255], as explained in section II.D, equation (A). This way, six properly encoded commands (according to an established protocol) are sent one by one to the hand via serial port, making each finger move towards the target position. Obviously, after observing the hand behavior during grasps, some manual calibration operations turned out to be necessary to make the fingers span over their complete range of motion and to achieve a more natural movement. Moreover, we compared the CyberHand and the virtual hand [6] giving them the same x y input signals at the same time, and they seemed to behave in a very similar way. Figure 1 shows a discrete x y grid and how the hand behaves when moving the mouse pointer over different areas of the screen.

Fig. 2. The CyberHand during two grasping tasks (lateral and cylindrical) driven by the mouse cursor motion over the monitor screen.

After a movement command is received, the hand control system sends back to the computer the corresponding finger cable tension value and the position value measured by the encoder. As a matter of fact it can be useful to keep track of how tension on the five tendons and the six position values evolve in time during a grasp, with respect to the mouse cursor position (x, y) used to drive the hand.

Since the significant trajectory is the one bringing the hand from an initial state (i.e. open hand in a relaxed-like position) to the object to be grasped, a neutral position area was established on the screen (left bottom corner), where the mouse cursor x and y positions correspond to the commands to the motors which make fingers open. Thus, tensions and positions variation was analyzed starting from the hand-opened position and ending when a stable object grasp was observed.

Several trials have been performed using different objects (a small water bottle, a pen, a rectangular box, a thin cardboard, a spherical ball) and trajectories, tensions and positions in time were recorded and plotted using a MatLab (The MathWorks, Natick, MA, USA) script. In Figure 2 two grasping sequences are represented; Figure 3 shows tensions and positions variations corresponding to the lateral grasp.

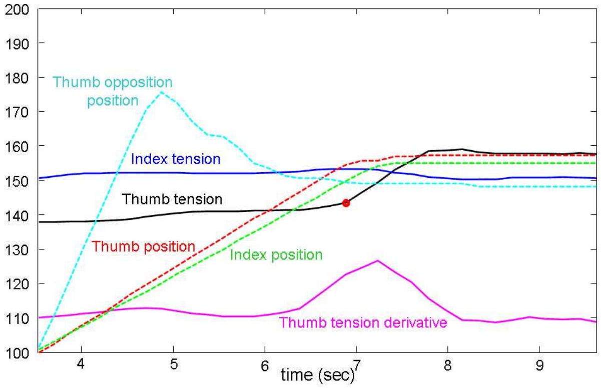

Fig. 3. Index and thumb cables tension and sliders position variations recorded during a lateral grasp, starting from the hand-opened configuration. Data are adimensional and related to the initial hand calibration. Tensions data are properly rescaled in order to fit the graph. The red marker on the thumb tension curve qualitatively indicates when the object comes in contact with the finger. Its derivative could be useful in the future to detect the contact event more precisely. At the same time we can observe that the index tension slightly decreases; this is caused by the interaction of the thumb through the object that tends to close it.

Particularly, once the user has learnt how to move the cursor in order to reach the object without useless tension fluctuations, the tension plots analysis could be very useful to implement in the future a tension threshold control, to be combined with the position one in order to optimize the grasp.

IV. CONCLUSIONS AND FUTURE DEVELOPMENTS

A prosthetic hand with many DoFs would require a lot of controlling inputs hardly manageable by the amputee. In this paper a new solution is proposed, which combines a mechanically achieved reduction of the number of necessary DoMs with a new control approach based on principal component analysis [6]. This method allows to use only two control signals to drive a 16 DoFs hand, and it has been tested onto the CyberHand, an underactuated robotic hand with only 6 DoMs. Experimental grasping trials show that the robotic hand can be controlled using a simple mouse cursor movement on the screen, whose x y coordinates modulate the first two principal components, PC_1 and PC_2, as it was done in early work on the virtual hand. These PCs are used to calculate 15 angular values which are then properly combined to obtain 6 position values and feed the motors.

Since the program driving the hand movements via serial port is able to acquire also tension and position values from the sensors on the hand, these data could be very useful in order to understand how to drive the prosthesis towards the object in the most correct way. Once the learning process has occurred, analyzing tensions plots and tension variations in the neighborhood of the grasping point will allow to identify a threshold to be used for tension control. The ultimate target of our work will be the setting up of a complete two channel EMG-based control system, creating an interface to modulate PCs with EMG signals; when the PCs map has been learnt by the user, it will then be possible for the subject to drive the robotic hand he/she is wearing.

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