An Adaptive Prosthetic Hand with Compliant Joints and EMG-based Control

Maria Chiara Carrozza, Franco Zaccone, Silvestro Micera, Giovanni Cappiello, Giovanni Stellin, Fabrizio Vecchi, Paolo Dario
ARTS Lab
Scuola Superiore Sant’Anna
Polo Sant’Anna Valderea
34 viale Rinaldo Piaggio
56025 Pontedera (PI), Italy
carrozza@sssup.it

Abstract – In this paper we present recent results about the experimental trials we are performing on a functional prosthetic hand characterized by an EMG-control and by a simple and low cost fabrication technology. A compliant under-actuated prosthetic hand has been designed and fabricated. The five-fingered hand (both palm and fingers) is moulded as a soft polymeric single part with compliant joints and embedded tendon driven under-actuated mechanism for providing adaptive grasp. The maximum measured cylindrical grasping force is 30 N. The one DoF prosthetic hand is controlled using two pre-amplified EMG electrodes. The proposed EMG-based control is a Finite State Machine (FSM). A particular attention has been given to the calibration phase. In order to identify the end of the grasp, the intensity of the current is monitored. Moreover, the microcontroller stops the motor when the average current overcomes the value imposed. Compared to other EMG based controllers, the approach proposed is very simple but it presents a good robustness and needs a minimum computational cost.

Index Terms – Biomechatronics, Prosthetics, Compliant joints, Under-actuation, Rehabilitation.

I. INTRODUCTION

In the last 30 years very innovative prosthetic hands have been developed. Nevertheless, from epidemiological analyses, it emerges that about 35% of the upper extremity amputees do not use their prosthetic hand regularly [1].

The reason can be found not only in the poor functionality of presently available prosthetic hands, but also to psychological problems, and is overstated by the modification of cosmetic appearance of the upper extremity.

The research described in this paper results from the experience achieved with a number of projects running at ARTS Lab, that have produced different hand designs, as described in previous papers (e.g., [2-4]).

The ultimate aim of the research in this field is to connect the artificial hand to the brain, but at present research efforts are still focused on the development of components, like neural interfaces, that represent real breakthroughs. Along with this research, there is plenty of space for improving the grasping ability and cosmetics of present hands in order to provide better prostheses for short term clinical application. To this aim, the research described in this paper is addressed at fulfilling cosmetic appearance requirements while keeping as low as possible the production cost, and in this framework a novel and simple fabrication process for prosthetic hands is proposed. A hand prototype has been designed, fabricated and tested in laboratory, and is almost ready for user trials. The basic design and fabrication technology have been partly described in [4].

The hand has only one active DoF (Degree of Freedom) obtained with a commercial motor and a tendon driven under-actuated mechanism that allows distributing the force among the fingers, by adapting the grasp to the object shape. All mechanisms are embedded in a “soft” silicone structure that provides cosmetic appearance and compliance. Finally, the hand prosthesis is controlled by EMG (Electromyographic) signals generated by voluntary user’s muscles contractions.

This paper summarizes the basic design approach, describes production process, it is then focused on the prosthetic hand control based on the processing of EMG signals and on experimental analysis.

II. THE PROTOTYPE

A. The Design Guidelines

The classic design approach in myoelectric prostheses is the intrinsic actuation, where all the actuators are embedded in the hand structure. The outcome of this approach is producing artificial hands with one (or a maximum of two) DOFs, which are able to provide a pinch force of about 100 N; in this case, the motion of the phalanges is determined at the design stage and therefore no grasping shape adaptation is possible, also because
of the rigid transmission [5]. On the contrary, if smaller actuators are used, the prosthetic flexibility can be raised and the DoFs can be increased [2]. Anyway, miniature actuators are quite far to offer a real alternative to standard electro-magnetic actuators. This is mainly due to the lack of suitable high torque micro-actuators and the difficulty to implement complex control scheme with a natural interface able to control all the DoFs.

In order to enhance prosthesis flexibility by keeping the intrinsic actuation solution and implementing simple control algorithm, we presented in [3] a design approach based on under-actuated mechanisms [6-7].

A mechanism is called under-actuated when it has less actuators than DoFs; traditional actuators (i.e. electro-magnetic motors) are replaced with passive elastic elements and mechanical stops. These elements can be considered as passive actuators, which cannot be controlled. In order to increase the number of DoFs without increasing the user’s cognitive burden, we exploited the under-actuation concept as in the Hirose’s paper [6]: each finger has 3 DoFs (3 phalanges). The cable is fixed on the fingertip and runs around the idler pulleys in the joints. A DC Motor pulls the cables which flex the fingers, as the flexor digitorum profundus. When the motor releases the cables, torsion springs in the joints extend the finger.

Inspired by the human hand, these prostheses have metallic phalanges and pulleys acting as the human skeleton, an actuation system (DC motor(s)) in the palm or in the forearm as muscles and a transmission cable system as the flexor tendons. Both the sensory and the control systems have also been implemented.

Compliant joints, on the other hand, are made up of one continuous part which deforms properly in certain areas in order to achieve motion. As a compliant flexible member bends, the external energy is stored in the form of strain energy. This stored energy is similar to the strain energy in a deflected spring, and the effect of the spring may be integrated into a compliant mechanism design [8].

The main drawback of compliant joints is the relative difficulty in analyzing and designing compliant mechanisms. The main advantages of the compliant joints are cost reduction (part-count reduction, reduced assembly time and simplified manufacturing process) and better performance. Weight and maintenance are decreased; nevertheless reliability and precision in small joints are higher. Also wear and lubrication are reduced; as the mechanism needs fewer mobile joints to carry out the same task. Some of them may be manufactured from a mouldable material and be constructed only of the same piece. Some innovative and promising examples of artificial hands based on compliant joints have been developed in the recent past [9-12] but they still have several assembled components, in general made out of different materials, driving their synergy in order to get the motion thanks to different stiffness.

The hand presented in this paper is moulded as a single piece of the same soft material, in order to allow a simple and low cost production process, thus resulting in a novel methodology to get compliant joints in a unique compliant structure. At this time, the analysis and synthesis processes are so complex and only experimental analysis of the solution adopted validate our works. The results obtained so far are encouraging and led us to fill a patent for further industrial development.

B. The soft hand

The prosthesis has got a really anthropomorphic appearance and kinematics, even if its structure is quite simple. The hand has four articulated fingers, each finger has three joints, but the opposable thumb has two joints. It is possible also to make the palm adaptive to the object, hollowing it between the index and the middle and the thumb.

A DC motor, with its gearbox and a power-off brake, provides the winding of a cable on a reel and its releasing, which in turn moves a slider pulling the five tendons, one for each finger. Both the actuation and the transmission systems are placed inside the palm. There is more than a simple connection between the tendons and the fingers. The phalanges are flexed when the cable is pulled but, after the first finger touches the object to grasp, a differential mechanism, based on the same cable, allows a further stroke of the slider. When the cable is released the elasticity of the material extends the finger.

There are 10 DoFs and one actuator. Pinch grasp and cylindrical grasps are allowed; under-actuated grasping mechanism does not provide any manipulation task.

The specific force distribution to each finger changes depending on the grasp type. So every phalanx joint has to be shaped properly in order to exploit the output power share as similar as possible to the natural hand. Moreover, by adapting each finger impedance, it is possible to drive their order of movement. This makes the grasping action definitely more anthropomorphic and stable.

When the hand closes, a further balancing differential mechanism distributes the force between the different fingers and makes the grasp further adaptive. As a finger touches the object first, the others keep on moving for a little, making the grasp involving all the fingers. At the same time, the actuation gear system increases the torque and decreases the closing speed, in order to augment the stability. So this under-actuated prosthetic device can perform an automatic finger wrapping around the object without any intervention of the user and above all without the need for dedicated sensors embedded in the phalanges.
C The EMG-based control

The prosthetic hands can be controlled by the user thanks to an EMG-based discrimination algorithm. Using EMG signals recorded from the upper limb muscles is a common and simple approach for controlling active prosthetic hands [13]. In fact, surface electrodes are easy to use and manage, do not require any surgery and do not impair forearm movements.

However, it is important to point out that EMG signals permit the control of few degrees of freedom (generally, no more than one or two active DoFs) and, above all, the user’s interface must be very friendly and handy in order to enable practical long-term use of the device. In fact, the user cannot be productive if she/he must spend a large portion of her/his energy and concentration controlling the artificial hand.

Therefore, a very simple and robust EMG-based algorithm able to control opening and closure of the hand has been developed.

This control algorithm is focused on the idea of using surface EMG signal detected from voluntarily activated muscles in order to generate the input signals for the simple Finite State Machine (FSM).

For this reason, a microcontroller of Microchip (PIC16F876) equipped with a 10-bit Analog-to-Digital (A/D) Converter module has been used in order to acquire and digitalize EMG signals extracted by using a couple of surface commercial electrodes (Otto Bock, 13E125 Myobock Electrode) placed on two antagonist muscles (e.g., biceps and triceps brachialis, or flexor and extensor of the forearm, depending on the level of the amputation).

In order to generate the two digital inputs for the FSM, a simple algorithm compares the EMG signals with two different voltage levels (threshold $V_{TH1}$ e $V_{TH2}$).

In particular, during the calibration phase, the microcontroller measures the EMG signals without muscular activity ($V_{BL}$) and calculates the activation thresholds ($V_{TH1}$ e $V_{TH2}$) for the two antagonist muscles selected with the following formulas:

\[
V_{TH1} = V_{BL} + \Delta V_{TH1} \\
V_{TH2} = V_{BL} + \Delta V_{TH2}
\]

in which $\Delta V_{TH1}$ e $\Delta V_{TH2}$ are fixed values set in empiric way. Nevertheless, these two parameters are stored in an electrically erasable programmable read-only memory (EEPROM) of microcontroller and can be changed via software in order to allow an on-line tuning.

Obviously, the choice of $\Delta V_{TH1}$ e $\Delta V_{TH2}$ affects the signal processing: a low threshold is more noise sensitive, a high one could be less precise in detecting fine movements.

Moreover, a software hysteresis has been developed in order to avoid the generation of false input signals. The use of hysteresis greatly improves noise immunity. In fact, without hysteresis, slow rising or noisy inputs may cause oscillations occurring while the slow rising input signal crosses through the input threshold. Such oscillations can cause false triggering leading to FSM reliability problems.

By the means of an added hysteresis, the digital input will not trip high until the input signal crosses an upper voltage threshold ($V_{TH-Rise}$) and will not trip low until the input signal crosses lower voltage threshold ($V_{TH-Fall}$) as showed in Fig. 2.

![Fig. 2: Generation of input signal for FSM](image)

The EMG-based control proposed is a simple Finite State Machine (FSM) showed in Fig. 3.
The starting state (S0) of this algorithm is dedicated to the calibration phase (initialisation of FSM). After $\Delta T$ ms, the FSM goes in the state S1. In this state the opening of the prosthetic hand begins: the microcontroller sends the enable signal and directions signals to a high voltage, high current dual full-bridge driver (L298). A Hall-effect switch is used to detect motor stop during the opening of the hand. The FSM remains in the state S1 until the EMG signal produced by flexor contraction of the forearm does not overcome and drop under its relative threshold $V_{TH1}$ (generation of the EMG logic pulse shown in Fig. 2). When it happens, the FSM advances in the state S2. In this state, the closure of the hand begins. In order to identify the end of the grasp, the intensity of the current is monitored. The current flowing through motor comes out from the bridge at a resistor. This acts as a sense output for detecting the intensity of this current. This sense output voltage is filtered with a 2nd order Butterworth low-pass filter, amplified and sent to a microcontroller (in Fig. 4 is showed the conditional circuit and in Fig. 5 the waveform of the current during a repetitions of closure and opening of the hand).

The microcontroller stops the motor when the average current overcomes 270 mA.

The FSM remains in the state S2 until the EMG signal produced by extensor contraction of the forearm does not overcome and drop under its relative threshold $V_{TH2}$ (generation of the EMG logic pulse shown in Fig. 2). Compared to other EMG based controllers, the approach proposed is very simple but it presents a good robustness and needs a minimum computational cost.

In order to allow “a control of the force” during the closure, it is possible modified the FSM in the following way: the closure of the hand begins when the EMG signal produced by flexor contraction overcomes the threshold $V_{TH1}$ and stops when the EMG signal falls under . In this way the patient can control the grasp force changing the duration of digital input. Of course, the controller stops the motor when the average current overcomes the value imposed also in this working mode.
This method has been tested with four different able-bodied subjects proving very good results in terms of controllability of the prosthesis (more than 98% of correct classification during the test phase).

![The control unit with battery and EMG electrodes](image1)

III. THE EXPERIMENTAL RESULTS

The innovative prosthetic hand has been evaluated with an appropriate experimental protocol. The whole structure is obtained by a single casted part of soft material and the mechanical components are reduced for obtaining an anthropomorphic articulated prosthesis based on a single compliant joint structure. Because of this non-conventional technology, the hand has some unpredictable behavior, and thus the experimental phase and fatigue/duration tests are a mandatory step before the user trials.

The experimental tests are aimed at assessing grasping ability of the hand in the two fundamental configurations: pinch grasp for 20 mm diameter objects and cylindrical grasp of object of diameter up to 80 mm.

In addition, as it is shown in Fig. 5, the resulting grasping force has been measured with a dedicated experimental set-up based on a commercial load cell ( Vishay Tedea Huntleigh, Basingstoke UK), in order to evaluate the force exerted during a palmar grasp.

The EMG control, as it has been implemented for prosthetic purposes, set the force at 13N with a current threshold value of 270 mA. By-passing this limit, we pushed the prosthesis up to 30N, with a threshold of 750mA. The mechanical limit has not reached yet, because the motor current limit is 900mA and the cable bears up to 50N; both the materials used have not shown any stress problem. The critical point seems to be the wear (particularly for cable) rather than the maximum load.

![The experimental set up for maximum force exerted](image2)

In order to prevent failures during the product operation, fatigue tests have been planned and an appropriate experimental test-bench has been fabricated. A grasp cycle with four different thicknesses, carried on 1000 grasp, will simulate prosthesis operation; this set-up has been designed with the Prosthetic Centre advice according to the objects normally grasped during activities of daily living. To this aim, the hand grasped a rotating cross with four different thicknesses on each arm: a counter takes out the number of grasps occurring before a failure event. Setting the grasping force at 15 N, the prosthesis performs 1668 grasp tasks in the first test and 1589 grasp tasks in the second.

Furthermore, we can compare some grasping tasks with the Otto Bock Prosthesis. The latter one is able to exert 89N during a cylindrical grasp. However, thanks to the increase contact area, the Soft hand is able to achieve similar results in terms possible grasping tasks even if it can exert a lower grasp force. As shown in Fig. 6, the Soft Hand performs an enveloping grasp wrapping all the phalanges around the conical object. On the
contrary, the Otto Bock Prosthetic hand has few reduced contact areas. The large amount of power grasp is wasted because of the little contact areas. The articulated compliant hand can perform the same stable grasp with a lower force level.

Fig. 6: The enveloping grasping of the Soft and compared with the grasp of a commercial prosthesis with rigid transmission

IV. CONCLUSION

This paper presented the Soft Hand, a prosthetic hand made out of a single production process based on soft material casting. It provides adaptive grasp functionalities thanks to an under-actuated tendon driven mechanism controlled by a single actuator embedded in the hand palm. The prosthesis is endowed with an EMG control. The finger dynamics are driven by the means of a cable tendon system, and purposely shaped joints providing a cosmetic appearance and motion. An extensive experimental testing activity is in progress for assessing the design and the engineering solutions before going to user trials. The first results of the grasping force and fatigue trials are encouraging and have showed us new guidelines for redesigning the prototype. Eventually, the obtained results will be exploited in the field of body powered hand prosthesis for obtaining low cost devices for humanitarian applications.

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