Hand Prosthesis Prototype Controlled by EMG and Vibrotactile Force Feedback

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Abstract- In the last 30 years very innovative prosthetic hands have been developed. Nevertheless, most of prosthetic hands are basically simple grippers with one or two degrees of freedom (DOFs) providing low functionality. Efforts have been made to improve the performance of devices so that they are as similar as possible with the human hand by exploring recent progresses in mechatronics technology. A major challenge in the development of prosthetic hands with a greater number of DOFs and, consequently, better functionality is to unite the entire system in a compact and lightweight design, besides provide some sensorial information to the amputee. The goal of this work is to develop a prosthesis concept which brings several advantages such as: lightweight, low energy consumption, reduction in volume, simple control and flexibility. In addition, the system is able to provide prehension force feedback. The mechanical design of a finger is described, which composes an artificial hand prototype of two active fingers, with three DOFs each one, and a static thumb. A force sensor provides feedback to the user through mechanical vibrations, ensuring greater safety to grasp an object. Also, a myoelectric control is implemented such that amputees are able to control their artificial limbs in a more natural way.

I. INTRODUCTION

The hand is one of the most important parts of the human body. In fact, thanks to his dexterity, is responsible for a large number of activities of daily living and allows the execution of gestures for social interaction [1]. Hand loss generates both psychological trauma and functional impairment, because the subject becomes unable to perform most daily tasks and baffled by the change in his appearance [2].

Hand prostheses are artificial devices used to replace the lost limb and are designed to restore as much as possible the function of a natural hand and its appearance. In the development of a prosthetic hand design some factors must be taken into account. The main requirements are: low complexity of construction and control, low size and weight, low power consumption, easy to handle, ability to grip objects, low cost, anthropomorphism and others [3, 4]. Moreover, it is highly desirable that artificial hands could present some sort of sensory system since artificial hands have no sensitivity, further improving its functionality and usefulness. For this reason different types of sensors can be used, such as slip, temperature and force sensors, providing feedback to the amputee.

One of the biggest obstacles to the development of prostheses is to obtain an integrated system, composed by actuators, drive systems, power sources, sensors and controllers in a compact and lightweight design. The size of all its components should be similar to the size and shape of a human hand, and also be as light as possible. Several studies of prosthesis designs have been developed to achieve such objectives [5-10].

The "Manus Hand" [5] is a multi-functional prosthesis that uses an underactuated mechanism composed by a system of pulleys and crossed tendons that allows both finger phalanges and inter-finger coupling movements. Moreover, thumb movements are coupled trough a Geneva-wheel mechanism, providing movements in two planes using only one actuator. In the "Spring Hand" [9] the fingers are composed by an underactuated mechanism based on cable transmission. The mechanism comprises three cables, one for each phalange, and two compression springs, one in the proximal phalange and other in the middle one. The adaptive behavior of each phalange, to guarantee the shape adaptation for the grasped object, is provided by the springs. In [10], several types of actuators and mechanisms that can be used in hand prostheses are shown, listing their main characteristics, applications, advantages and drawbacks.

Force control for hand prostheses is important to guarantee the execution of accurate and delicate movements. Some works that deal with this kind of control are reported in the literature. In [11], force control feedback is provided through cable tension sensors, which are fixed in the tendons of each finger. The global grasp force is calculated by summing all finger forces involved in griping and the desired force is selected according to the shape and weight of the object to be held. However, only two possible desired force levels are allowed, for each grasp type that the prosthesis can execute. In [12] Force Sense Resistor (FSR) and slip sensors were installed in the finger. Force sensor quantifies the applied force and slip sensor detects if raising applied force is needed. Chappell and Elliott [13] proposed a contact sensor for artificial hands that uses capacitance effects to measure strain. Force sensors for hand prostheses application must be small, robust, low power, cheap and easy to install [13]. However, it requires some space on the finger surface, can only measure forces applied directly over the sensor, supposing that it is the contact point, increases complexity of

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the system and may need repeated calibration, specially due to temperature effects.

This paper presents the development of an underactuated mechanical finger that composes an artificial hand prototype of two active fingers with three DOFs each, and a static thumb, which is controlled by electromyography (EMG) signals. Underactuated mechanisms have fewer actuators than number of DOFs. In our case, six degrees of freedom are driven by a single motor. This mechanism applied to hand prosthesis brings several advantages such as those mentioned before: lightweight, reduction in volume, less complexity of control and still allows a good functional flexibility. The proposed mechanism allows that if one of the fingers' phalange is restricted, the others continue moving. At the end of the movement the phalanges adapt themselves to the shape of the object allowing a good grasp. A two finger prototype hand is shown. It was designed based on anatomical characteristics of the human finger and both fingers are coupled by a differential mechanism.

The prototype comprises also a force sensor which provides the user a vibration signal feedback attached to the amputee, ensuring greater safety to grasp an object, , such as other prosthesis designs [14, 15]. The actual force applied by the finger is estimated indirectly from motor current level. Using this signal to infer contact force is simple, compact, low-cost and provides an overall estimation of contact force. It has been applied in other works [e.g. 16] not, however, for hand prosthesis, in our information.

The control interface between amputee and artificial hand is performed through EMG signals, where muscular commands are responsible to control both open and close movements of the hand.

II. MATERIAL AND METHODS

A. Mechanical Design of the hand prototype

The hand prototype is equipped with two active fingers, with three DOFs each, and a static thumb. Furthermore, the system composes one actuator and a differential mechanism to join both active fingers. The proposed finger has three phalanges: proximal, middle and distal, and their lengths were based on size similar to index finger of a human, according to [17].

Each phalange is rigidly connected to a pulley located in its proximal joint. Each pulley is associated to a finger joint: metacarpophalangeal (MP), proximal interphalangeal (PIP) and distal interphalangeal (DIP). The proximal phalange is connected to a fixed base, through the MP joint, called metacarpus. A pulley responsible for the movement of the joints is called drive pulley and is fixed on the metacarpus (Fig. 1a). An inextensible wire is fixed on the tip of the distal phalange and conducted to the drive pulley by passing around the other pulleys. Mechanical stops are used to avoid hyperextension.

Two parallel and opposed driving chains were installed in the finger, using the same pulleys. One chain performs flexion and the other extension. Here, differently from the RTR-II finger [18] for example, which has only active flexion with extension driven by springs, both movements are active when the motor turns forth and back. In this way, no torque is wasted to deform a spring.

During the unconstrained motion, the finger behaves like a single rigid body in rotation about a fixed axis, namely the most proximal joint. When the first finger phalange reaches some external obstacle and the motion is constrained, the second phalange starts to move with respect to the former, until it touches the object. Finally, the distal phalange moves with respect to other phalanges and the finger is fully contacted with the object. During this phase, the actuator shall produce the required force to hold the object. The final geometrical configuration of the finger will be determined by the external constrains, related to the shape and stiffness of the object to grasp.

A differential mechanism, which has one input and two outputs, connects two identical fingers through their respective drive pulleys (Fig 1b). Therefore, the only actuator connected to the mechanism is one driving input. More details of how it mechanism works can be viewed in [19]. A Futaba S3305 Servo was used to drive the mechanism. Its body was fixed to the prototype and the shaft fastened on the differential mechanism.

B. Finger Kinematics

The mechanical finger proposed is an open kinematic chain and its final geometrical configuration will be determined by the external constrains, related to the shape and stiffness of the object to be grasped.



Figure 1. (a) Finger design; (b) Connection between the fingers

 Θ_1 , Θ_2 and Θ_3 indicate the proximal, middle and distal phalange rotations, respectively, so that they are 0 degrees when the finger is fully extended, and r_1 , r_2 and r_3 are the pulleys radius of proximal, middle, distal joint. Θ_m and r_m are the driving pulley rotation angle and radius, respectively.

The angular position of every phalange Θ_i , with i=1, 2, 3 is related to the driving pulley angular position Θ_m through the following relations.

During the unconstrained motion:

$$\Theta_i = \Theta_m * r_m / r_i$$
 $i = 1, 2, 3$ (1)

and

$$\Theta_1 = \Theta_2 = \Theta_3 \tag{2}$$

When the phalange i touches the external constrains:

$$d\Theta_i/dt = 0 \tag{3}$$

and

$$\Theta_{i+1} = \Theta_i + \Theta_m * r_m / r_{i+1}$$
 $i = 1, 2, 3$ (4)

In order to evaluate the ability to grasp, a static thumb with 20 degrees of flexion was placed in opposition of the two fingers (Fig. 3).

C. EMG Interface

In order to control the prosthetic hand prototype surface EMG signals are used. Brachial biceps delivers the intention to flex the finger, while triceps commands finger extension. Prosthesis commands comprehend open, close and stop motions.

In order to eliminate most of noise, differential electrodes configuration is employed, placed according to [20]. To further eliminate undesired noise, a 4th order 20-500Hz bandpass analog Butterworth filter is used. Further full-wave rectification and low-pass filtering generate an EMG envelope, which amplitude is related to muscle activation level. The resulting signal is digitalized by a PIC18f4550 microcontroller that also to generates a PWM signal to drive the actuator. The signal is finally normalized by the maximum voluntary contraction (MVC) EMG, collected from a separate trial.

D. Myoelectric Control

The strategy control implemented in the hand prototype works as the follows: when the amplitude level of the normalized EMG responsible for the close movement exceeds a threshold, in this case 20% of the MVC and, at the same time, the amplitude of the EMG signal from the other muscle responsible to the open movement - is below the threshold value, then the hand starts to close. When the opposite occurs, the hand starts to open. In the case where both signals exceeds the threshold, or both have theirs EMG amplitude below the threshold the finger remains in the current position. In this way, to keep an object grasped the user does not need keep the muscle contracted.

Servo actuator reference angle is provided by the PWM signal generated by the microcontroller, with 50Hz frequency and 1-2% duty cycle. The minimum value of the duty cycle represents the 0 degrees position of the actuator (fully opened hand) and the maximum duty cycle represents 200 degrees (fully closed hand). The actuator angular position resolution is one degree.

When the system is turned on, the hand moves to full extension (0 degrees). If the user activates the muscle group responsible for the closing movement, the duty cycle starts increasing so that the motor angle will be incremented and the hand begins to close. Similarly, when the antagonist muscle group is contracted the duty cycle starts to decrement from its current value and the hand begins to open. The Fig. 2 shows the flowchart of motion strategy control implemented in the microcontroller.

E. Force Feedback

The actual force applied by the hand over the object is estimated indirectly from actuator current level. This variable is measured by a shunt resistor in series with the actuator. The use of this simple, compact and low-cost method provides an overall estimation of contact force and was exploited and compared to a direct force measurement with a Force Resisting Sensor (FSR), as can be viewed in [21].

The feedback vibration system uses an unbalanced DC micromotor, typically used in cell phones vibration alert. The vibration intensity is modulated through a PWM signal with 700 Hz frequency and variable duty cycle (20-100%), generated by the microcontroller. The duty cycle modulates vibration amplitude and is controlled by the servo current. To observe the variation of vibration amplitude according to the applied force, a small bench with an accelerometer was used and tests during grasp tasks were performed.

The feedback device can be placed anywhere on the body that the user wants.



Figure 2. Flowchart of motion strategy control

III. RESULTS AND DISCUSSION

To build the hand prosthesis prototype, distal, middle and proximal phalanges were machined in aluminum with dimensions of length equal to 4.5, 3.0 e 2.4 cm, respectively, and pulleys and thumb in Delrin[®] (DuPontTM) acetal plastic resin. In Fig. 3 the mechanical hand prototype with 2 active fingers and a static thumb can be observed. The thumb is located in opposition to the others fingers. Even through it is static, it allows the hand improve the grip to hold objects. The overall weight of the hand is about 300g.



Figure 3. Hand prototype



Figure 6. Current signal and vibration amplitude of the system feedback

IV. CONCLUSION

An underactuated finger system mechanism prototype for hand prosthesis was proposed and tested. The main goal of the design was increasing prostheses flexibility without increasing the number of actuators and control complexity.

The prototype has two active fingers with 3 DOFs each and a fixed thumb, driven by a single actuator. The device also attempts to incorporate design requirements of anthropomorphism, low weight, low power consumption, low cost, ability to grip different objects and provide force feedback.

The obtained results seem promising, but there is still room for improvements. Finger movements during grasping tasks will be further investigated, with the aim of achieving by the artificial fingers a more realist behavior if compared to their natural counterparts.

Vibrotactile feedback of grasping force using a unbalanced micromotor is also a simple and useful functionality. Feedback system incorporating others sensorial information, such as temperature and slippage detection is also a room for improvement.

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REFERENCES

- E. Y. S. Chao, K. An, W. P. Cooney, R. Linscheid, "Biomechanics of the hand", Teaneck, NJ. USA: World Scientific Publishing Co. Pte. Ltd., pp. 5-75, 1989.
- [2] J. Pillet, A. Didier, "Aesthetic hand prosthesis: gadget or therapy? Presentation of a new classification", Journal of Hand Surgery, British and European Volume, p. 523-528, 2001.
- [3] D. J. Atkins, D. C. Y. Heard, W. H. Donovan, "Epidemiologic overview of individuals with upper limb loss and their reported research priorities", Journal of Prosthetic and Orthotics, vol. 8, num. 1, pp. 2-11, 1996.
- [4] J. L. Pons, R. Ceres, E. Rocon, D. Reynaerts, B. Saro, S. Levin, W. Van Moorleghem, "Objectives and technological approach to the development of the multifunctional manus upper limb prosthesis", Robotica, v. 23, n. 03, p. 301-310, 2005.
- [5] J. L. Pons, E. Rocon, R. Ceres, D. Reynaerts, B. Saro, S. Levin, W. Van Moorleghem, "The manus-hand dextrous robotics upper limb prosthesis: mechanical and manipulation aspects", Autonomous Robots 16, p. 143-163, 2004.
- [6] C. Cipriani, M. Controzzi, M. C. Carrozza. "The SmartHand Transradial Prosthesis", Journal of NeuroEngineering and Rehabilitation", vol. 8, no.29, 2011.

To demonstrate the potential of the mechanism, Fig. 4 shows the hand grasping an object. It can be noticed that the fingers are able to adapt itself to the shape of the object. Phalanges of both active fingers have different tracks until the hand is fully contacted with the object.

A different situation, when only one finger is restricted by an object, and the other one remains free, was also tested to observe the functioning of the underactuated mechanism (Fig. 5). An object was positioned on the thumb so that, when the fingers are flexed, only one of them is restricted by the object. It can be noticed that, even if the hand mechanism has only one actuator, the final position of the phalanges are independent, depending only on the shape of the object.

To test vibration amplitude of force feedback according to the applied grip force, a compliant object was grasped by the prototype. Both actuator current signal and acceleration signal of the feedback system were acquired. The Euclidean norm of the three-axis accelerometer output channels is shown in Fig. 6. It can be observed that vibration and current amplitudes are related with each other. Since in [21] authors suggested that the feedback force would be useful in prosthesis designs, this device sounds be effective to provide the force applied on the object.

It is important to highlight that in all tests the control of the prosthesis was performed by means of the EMG signal through interface control.



Figure 4. Hand grasping an object



Figure 5. Hand grasping an object with only one finger

- [7] S. A. Dalley, D. A. Bennett, N.A. Alshammary, and M. Goldfarb, "Multigrasp hand prosthesis and myoelectric control method for enhancing the functional capability of upper extremity amputees" IEEE LifeSciences Newsletter online, Nov. 2012.
- [8] J. Yang, E. P. Pitarch, K. Malek, A. Patrick, L. Lindkvist, "A multifingered hand prosthesis", Mechanism and Machine Theory 39, p. 555 581, 2004.
- [9] M. C. Carozza, C. Suppo, F. Sebastiani, B. Massa, F. Veccchi, R. Lazzarini, M. R. Cutkosky, P. Dario, "*The spring hand: development of a self-adaptive prosthesis for restoring natural grasping*". Autonomous Robots 16, p.125-141, 2004.
- [10] V. O. Del Cura, F. L. Cunha, M. L. Aguiar, A. Cliquet Jr. "Study of the different types of actuators and mechanisms for upper limb prostheses". Artificial Organs 27 507–16, 2003.
- [11] C. Cipriani, F. Zaccone, G. Stellin, L. Beccai, G. Cappiello, M. C. Carrozza, P. Dario. "Closed-loop Controller for a Bio-inspired Multifingered Underactuated Prosthesis". Proceedings of the 2006 IEEE International Conference on Robotics and Automation. Orlando, Florida - May 2006
- [12] V. O. Del Cura. "Acionamento e controle de dedo de uma prótese para membro superior com realimentação proprioceptiva de força e temperatura". Master Dissertation USP, Escola de Engenharia de São Carlos, 2005
- [13] P. H. Chappell and J. A. Elliott. "Contact force sensor for artificial hands with a digital interface for a controller". Measurement Science and Technology, 14. pp. 1275-1279. ISSN 1361-6501, 2003.
- [14] C. Cipriani C, F. Zaccone, S. Micera, M. C. Carrozza. "On the shared control of an EMG-controlled prosthetic hand: analysis of userprosthesis interaction." IEEE Trans. Robot. 24(1), 170–184, 2008.
- [15] C. Pylatiuk, A. Kargov, S. Schulz. "Design and evaluation of a lowcost force feedback system for myoelectric prosthetic hands." J. Prosthet. Orthot. 18(2), 57–61, 2006.
- [16] Li X., and Li H. X. Fuzzy Estimation Of Feed-Cutting Force From Current Measurement - A Case Study On Tool Wear Monitoring. IEEE Trans. Systems, Man, and Cybernetics Part C: Applications and Reviews, Vol. 2, No. 3 2004, pp.299-311.
- [17] V. Bundhoo, E. J. Park, "Design of an artificial muscle actuated finger towards biomimetic prosthetic hands". Proceedings of the IEEE International Conference on Advanced Robotics, Seattle, pp. 368-375, WA, 2005.
- [18] B. Massa, S. Rocella, M. C. Carozza, P. Dario, "Design and Development of an Underactuated Prosthetic Hand". Proceedings Of The Ieee, Washington, 2002.
- [19] K. Nice, "How Differentials Work" Howstuffworks. 17 Oct. 2005 http://auto.howstuffworks.com/differential.htm>.
- [20] SENIAM Surface ElectroMyoGraphy for the Non-Invasive Assessment of Muscles. Available in http://www.seniam.org/.
- [21] T. S. P. Sono, L. L. Menegaldo, "Myoelectric Hand Prosthesis Force Control Through Servo Motor Current Feedback", Artificial Organs, V. 33, P. 871-876, 2009