DESIGN OF AN ANTHROPOMETRIC UNDERACTUATED MECHANICAL FINGER FOR HAND PROSTHESIS

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Abstract. *The hand is one of the most important parts of the human body because it allows the execution of a large number of functions, such as: grip, perception, exploration, manipulation. It is able to adapt quickly to the shape of the objects in different ways, allowing both the handling of delicate objects and transport of heavy objects making it responsible for most of our daily activities.The loss of the hand generates trouble both psychological and functional because the individual becomes unable to perform most daily tasks as well as he is shaken by the change in his appearance.Prostheses are artificial components designed to replace a lost limb, recovering part of the functions that have been limited due to its loss In the last 30 years very innovative prosthetic hands have been developed. Nevertheless, due to unnatural movement, low functionality and cosmetic, high weight, insufficient grasp force, etc, in many cases the hand prosthesis is rejected by the patient. This paper presents the development of an underactuated mechanism for a mechanical finger that will be used for building of hand prosthesis. Underactuated mechanisms are mechanisms that have fewer actuators than the number of degrees of freedom. This way, three degrees of freedom of each finger are driven by a single motor. This mechanism applied to hand prosthesis brings several advantages such as: lightweight, reduction in volume, less complexity of control and still allows more flexibility when are compared with those on full actuation. The proposed mechanism allows that even if one phalange of the finger is restricted by an object the others continue moving so that at the end of the movement, the phalanges adapt themselves to the shape of the object allowing a good grasp.The mechanical design of the prototype of a finger has being developed. The prototype of the finger was designed based on anatomical characteristics of the human index finger. One reason for the choice of the index finger as a model is due to its characteristic of opposition with the thumb, which makes it be one of the fingers more active in various functions performed by hand. Furthermore, after that the mechanism of this finger is validated, it can be reproduced with small changes in the size of the phalanges to build others fingers and be placed in the structure of the palm of hand in order to build a whole hand.*

Keywords*: hand prosthesis, underactuated mechanism, mechanical finger*

1. INTRODUCTION

The hand is one of the most important parts of the human body because it allows the execution of a large number of functions, such as: grip, perception, exploration, manipulation. It is able to adapt quickly to the shape of the objects in different ways, allowing both the handling of delicate objects and transport of heavy objects making it responsible for most of our daily activities (Chao *et al.*, 1989). The loss of the hand generates trouble both psychological and functional because the individual becomes unable to perform most daily tasks as well as he is shaken by the change in his appearance (Pillet and Didier, 2001).

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 thus reducing the problems. 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 other (Atkins *et al.,*1996; Pons *et al.,* 2005).

One of the biggest obstacles to the development of prostheses to achieve some of the characteristics of the human hand is the integration of 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, weight and shape of a human hand.

It is a great challenge to meet all requirements in a single project prosthetic hand. Several studies of prosthesis designs are being developed to achieve these objectives. Some research designs of prostheses can be highlighted: “Manus Hand” (Pons *et al*., 2004), “São Carlos Hand” (Cunha *et al*., 2000), “Southampton Hand” (Kyberd *et al*., 2001), “Iowa Hand” (Yang *et al*., 2004), “Spring Hand” (Carrozza *et al*., 2004), etc.

Some prostheses are also commercially available, like the well-known Otto Bock Sensor Hand, the Utah Arm, and the i-Limb Hand from Touch Bionics, among others. However, commercially available low-cost hand prostheses often accomplish only simple movements with one or two degrees of freedom are heavy and do not reproduce satisfactorily the dexterity of the human hand. Usually, they are not able to adapt to different shapes of objects due to the lack of finger joints, providing only pinch movements. Therefore, some of them are used only for aesthetic reasons. As a result, about 35% of the upper extremity amputees do not use their prosthetic hand regularly (Atkins *et al*, 1996).

This paper presents the development of an underactuated mechanical finger that will be used for building of hand prosthesis. Underactuated mechanisms are mechanisms that have fewer actuators than the number of degrees of freedom. This way, three degrees of freedom of each finger are driven by a single motor. This mechanism applied to hand prosthesis brings several advantages such as: lightweight, reduction in volume, less complexity of control and still allows more flexibility when are compared with those fully actuation. The proposed mechanism allows that even if one phalange of the finger is restricted by an object the others continue moving so that at the end of the movement, the phalanges adapt themselves to the shape of the object allowing a good grasp.

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2. MECHANICAL DESIGN

The mechanical finger was designed in the SolidWork Software and after that, parts were machined and the prototype was built. The prototype of the finger was designed based on anatomical characteristics of the human index finger. One reason for the choice of the index finger as a model is due to its characteristic of opposition with the thumb, which makes it be one of the fingers more active in various functions performed by hand. Furthermore, after the mechanism of this finger is validated, it can be reproduced with small changes in the size of the phalanges to build all others 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 Bundhoo e Park (2005), with dimensions of length equal to 4.5, 3.0 e 2.4 cm, respectively (Figure 1).

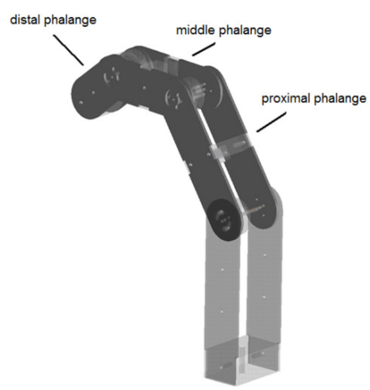


Figure 1. Proposed finger designed into SolidWork software

Phalanges are connected by pulleys so that each pulley is rigidly connected at the proximal part of each phalange and can rotate freely around the axis fixed on the distal part of the previous phalange (Figure 2).

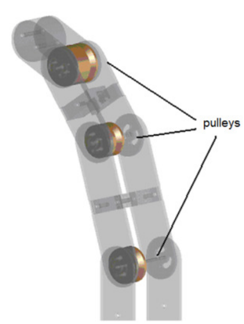


Figure 2. Pulleys

A non-elastic wire (tendon) is fixed on each pulley, and passing through guides are connected to a differential mechanism. The guides, shown in detail in the Fig. 3, are connected to the pulleys and align tendons with the central axis of the finger in order to prevent that wires pass by structure outside.

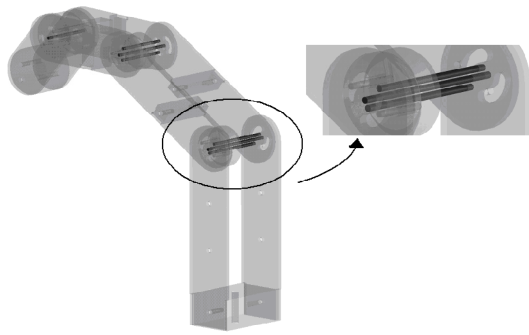


Figure 3. Guides

The same configuration to connect tendons was installed on the finger in an opposite and parallel way, using the same pulleys. Thus, when the motor rotates forward or backward the finger flexes or extends.

According to Bundhoo and Park, 2005, joints of the index finger have the following maximum amplitudes of flexion: 90 degrees at the metacarpal joint, 100 to 110 degrees in the interphalangeal joint and 80 degrees at the distal joint. Therefore, stop mechanism were installed into the finger design restricting the amplitude of flexion movement to 90, 100 and 80 degrees at the proximal, middle and distal joints, respectively. Figure 4 shows the detail of stop mechanism. The diameters of the pulleys were selected so that all joints could reach their amplitude limits at the same time when all tendons are actuated at the same speed.

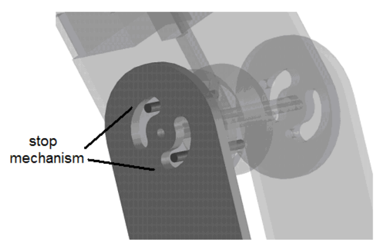


Figure 4. Detail of stop mechanism

In order to ensure spacing between the phalanges of the finger and still become the system more rigid spacers were placed on mechanical design (Figure 5).

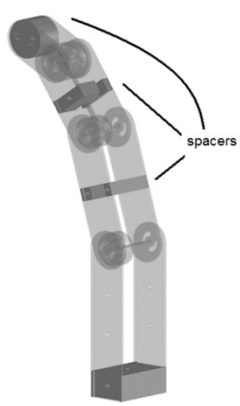


Figure 5. Spacers

3. DIFFERENTIAL MECHANISM SYSTEM

In order to reduce weight and size of prostheses a solution which has been studied by some designers is the use of underactuated mechanisms. Underactuated mechanisms are mechanical systems with fewer actuators than degrees of freedom (DOF). A finger with an underactuated mechanism has the capability to adapt its shape to envelope grasped objects although the finger is controlled by a reduced number of actuators. This is a very useful feature in grasping task with objects having various shapes and sizes. In addition, finger with reduced number actuators can be built with low-cost, weight, size and power consumption, and easy-operation features (Wu *et al*, 2009).

Actually, since underactuated mechanisms designed specifically for this purpose automatically adjust themselves to the shape of the object. It is not necessary to have a coordination of fingers movement, and, consequently, it is not necessary a coordination to control the motor. In this way, many of the requirements of prostheses designs can be achieved.

In this work, a differential mechanism system capable of controlling multiple DOFs with a single actuator was built by combining several differentials. The system, built here to operate one finger, is composed of two differentials (A and B) so that the output of one is connected to the input of other, as seen in Fig. 6, allowing the system has one input and three outputs (A'', B ', B''). So, each tendon is connected at each output of the differential mechanism.

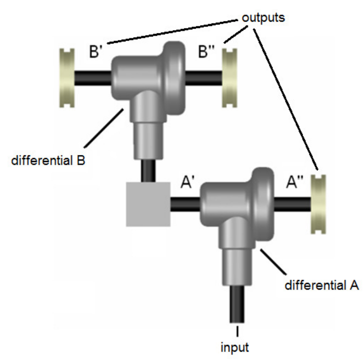


Figure 6. Schematic of differential mechanism system

This differential mechanism allows that phalanges move until they get in contact with an object or reaching its flexion limit. In this mechanism, even if the movement of one phalange is restricted by an object, others phalanges can move. This allows a complete adaptation of the finger with the object.

Here, unlike mechanical fingers proposed in the literature, where only the flexion movement is performed by the motor and the extension is accomplished by springs, both movements are performed when the motor rotates forward and backward. Thus, the torque produced by the motor will be transmitted directly to the finger, without it spends part of its torque to deform springs, as noted in existing mechanisms.

4. FINGER KINEMATICS

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

In the kinematics analysis the index finger was considered as in Fig. 7 - three segments that represent distal, middle and proximal phalanges - and both unconstrained and constrain movements of the finger were considered separately.

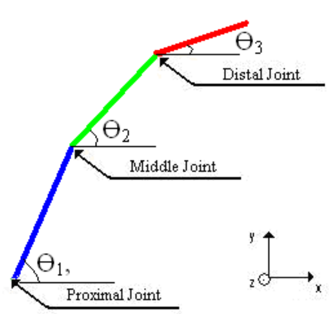


Figure 7. Finger representative

Θ_1, Θ_2 and Θ_3 indicate the proximal, middle and distal phalange rotations respectively with respect to the abscissa axis, and r_1, r_2 and r_3 are the pulleys radius of proximal, middle, distal joint. Θ_m and r_m are the actuator angular position and the pulley radius that are connected in each output of the underactuated mechanical system, respectively.

The angular position of every phalange Θ_i, with i=1, 2, 3 is related to the actuator angular position Θ_m through the relations:

- for unconstrained movements:

$$\theta_i = \theta_m * \frac{r_m}{r_i} \qquad (1)$$

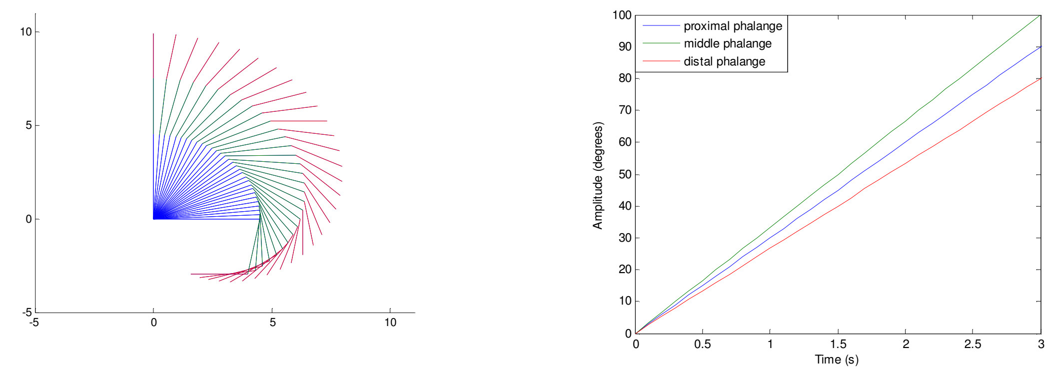
- when the phalange i touches an external constrain:

$$\dot{\theta}_i = 0\ ; \quad \theta_i = \theta_i \qquad for\ i = 1{:}\,i \qquad (2)$$

and,

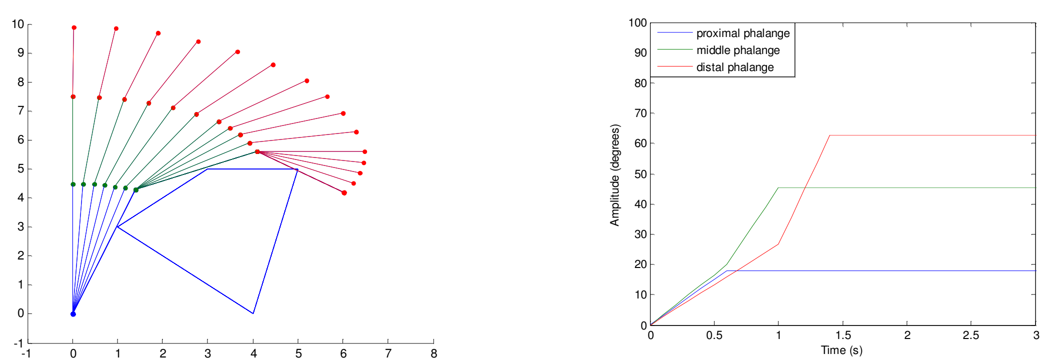
$$\theta_{i+1} = \theta_m * \frac{r_m}{r_{i+1}} \qquad for\ i = i{:}\,2 \qquad (3)$$

Some results from numerical computation have been plotted in Fig. 8 and 9, showing first the finger workspace during the unconstrained movement and after the constrained movement, both during flexion movement.



(a) (b)

Figure 8. (a) Simulation of flexion kinematical pattern; (b) Rotation angles of each phalange, unconstrained movement



(a) (b)

Figure 9. (a) Simulation of flexion kinematical pattern; (b) Rotation angles of each phalange, constrained movement

Values of pulleys radius affect the rotational angles during the closing sequence. These parameters were chosen in order to mimic the human finger movements, so that all phalanges reach their amplitude limits at the same time, in the unconstrained movement.

5. FINGER DEVELOPMENT/RESULTS

Following the design principle described previously, the mechanical finger has been built. Phalanges were machined in aluminum and pulleys in delrin plastic material. In the Fig. 10 can be viewed the mechanical finger prototype with 3 DOFs.

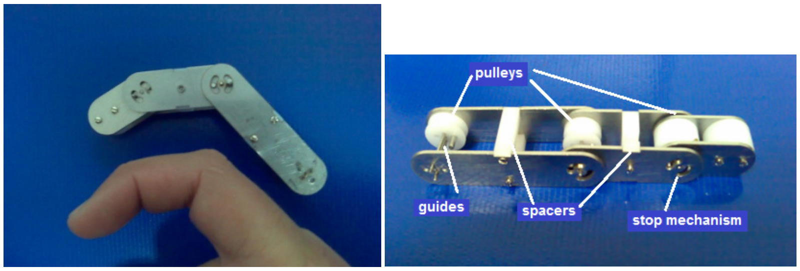


Figure 10. Finger prototype

The differential mechanism system was built using two differentials connected as described previously. Figure 11 shows the differential mechanism system prototype. A pulley, where each tendons pair is linked, is coupled in each output of system; while in the input an actuator will be connected.

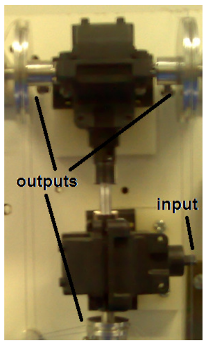
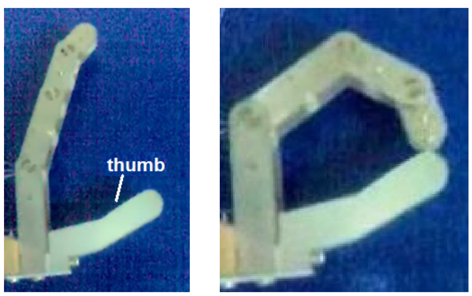


Figure 11. Differential mechanism system

To begin with, the system used differentials of reasonable size to verify the functioning and validate the system. After, the differential mechanism system will be built using differentials of reduced size.

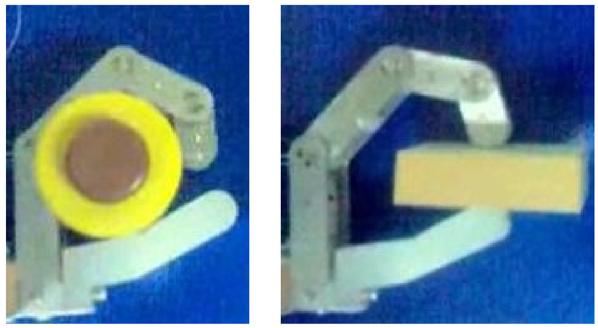
In order to evaluate the ability to grasp, a static thumb with 20 degrees of flexion (Figure 12a) was positioned in the prototype so that the tip of the index finger touches its tip during the unconstrained movement, as viewed in the Fig. 12b, performing, in this way, a pinch grasp. A base that represents a metacarpal bone was added to the prototype to support and connect both fingers.



(a) (b)

Figure 12. (a) Index and thumb finger prototype; (b) Unconstrained movement

Figure 13a shows the finger grasping an object. It can be noticed that the finger is able to adapt itself to the shape of object. Figure 13b shows the finger holding an object during a pinch grasp. It happens in a natural way because the finger flexes freely and stops moving when the distal phalange touches an object.



(a) (b)

Figure 13. (a) Finger grasping an object; (b) Pinch grasp

6. DISCUSSION AND CONCLUSION

The design approach based on underactuated mechanism was proposed and has been applied to the prosthetic field with the aim of increasing prostheses flexibility without increasing the number of actuators and control complexity.

The prototype is a mechanical finger with 3 DOFs that addresses prosthesis design requirements for an increase in functional grasping. The device also adds to the prosthesis design requirements of anthropomorphism, low weight, low power consumption – because the number of actuators is reduced, low cost, ability to grip objects and others.

The proposed kinematic model represented a useful tool for simulating the expected grasping capabilities besides choice of parameters values.

The finger can be reproduced with small changes in the size of the phalanges to build others fingers and be placed in the structure of the palm of hand in order to build a whole hand.

Suitable control strategies will be investigated in order to develop a user-friendly control interface for the prototype.

7. ACKNOWLEDGEMENTS

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9. RESPONSIBILITY NOTICE

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