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# DEVELOPMENT OF AN UNDERACTUATED FINGER MECHANISM FOR A HAND PROSTHESIS

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***Abstract.*** *This works shows the conceptual development of a finger mechanism for a prothestic hand. Three degrees of freedom of the finger are actuated by single DC motor, characterizing therefore an underactuated mechanical system. Mechanical torque developed by the motor is transmitted to the phalanges through tendons and is converted into flexion and extension torques by means of small pulleys. The tendon is fixed on the tip of the distal phalange and conducted up to the motor pulley by passing around each pulley. The chosen servo motor is able to provide movement of the finger phalanges at an acceptable speed, as well as a reasonable amount of prehension force.*

***Keywords****: hand prostheses, underactuated mechanism*

## 1. INTRODUCTION

The development of robotic hands has been one a largely explored area in mechatronics research. Robotic hands can be used to take place of human hands in dangerous work or as auxiliary devices for delicate work. In addition, robotic hands can be used as inspiration for designing prosthetic hands (Jacobsen et al., 1984; Mason et al., 1985; Butterfass et al., 2001). However, even though they afford flexible motion patterns with many degrees of freedom, most of robotic hands fingers have independent joint actuators for each articulation (Jacobsen et al., 1986; Londi et al., 2004) becoming a bulky mechanism, and therefore making it difficult to be used as a prosthetic hand.

Restricted space to install actuators and construction complexity are the most difficult problems in the design of hand prosthesis. Commercial prosthetic hands, particularly the most accessible from the economic point of view, use simple and easy to build mechanical designs, but are commonly not capable of adapting their fingers to the different shapes of the objects.

One possible solution to solve this problem is the application of underactuated mechanisms. Such mechanisms have less actuators than degrees of freedom. In addition, passive elements and mechanical stops are introduced in mechanism. Underactuated fingers involve the objects to be grasped and adapt to their shape although each of the fingers is controlled by a reduce number of actuators, usually one. After all, this kind of mechanism allows a more natural grasping of objects, when compared to independent actuation (Birglen, 2004). Finger movements the human hand is naturally underactuated and presents a certain amount of coupling among the degrees of freedom (DOFs).

A few underactuated fingers have been proposed in the literature. Some of them are based on rigid bar mechanisms (Dechev et al, 2001; Laliberte et al, 2000), while others are based on finger flexion through tendons and extension with springs (Crisman et al, 1996; Carrozza et al, 2004; Massa et al, 2002). In this work, a 3-DOF mechanism adapted from Massa et al. (2002) was build and a series of experiments was performed to analyze its behavior in the free and grasping movements. Here, two of the Massa´s and coauthors mechanism, developed at ARTS Lab at Scuola Superiore Sant'Anna, Pisa, Italy, are implemented in the same finger, using one single actuator, and thus allowing active flexion and extension of the finger without springs. By using springs, part of the torque delivered by the motor is consumed to deform the elastic elements in finger flexion, delivering this energy in extension. In this new configuration, no elastic elements like springs are necessary, increasing the net available torque to the finger.

## 2. CONCEPTUAL DESIGN

The mechanical design of the finger has been based on the robotic actuator Soft Gripper, an underactuated mechanism originally proposed by Hirose (1977). The mechanical finger is composed by three phalanges. Each phalange is rigidly connected to a pulley located in its proximal joint. In the phalange's distal joint, the following phalange is connected, with another pulley fixed in this phalange, and so successively. A non-elastic wire is fixed on the tip of the distal phalange and conducted to the motor pulley by passing around each one of pulleys (Figure 1) until reaching a pulley connected to the motor.

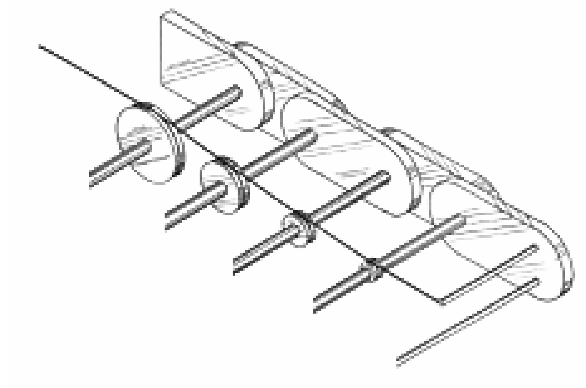

Figure 1. Mechanism of the finger (Hirose, 1977)

This mechanical finger is able to perform flexion or extension of the three phalanges using one single motor. Mechanical stops are used to avoid hyper-extension. 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.

Two parallel and opposed driving chains were installed in the finger, using the same pulleys. One chain executed flexion and the other extension. Here, differently from the ARTS finger (Massa et al. 2002), that has only active flexion with extension driven by springs, both movements are active, when the motor turns forth and back.

Commercial servo-actuators used in RC-planes were used to drive the mechanism. This kind of actuator is highly suitable to the desired application, due to the low cost, high torque, low energy consumption and simplicity. To control the prosthetic finger, it will be necessary to develop an interface which allows the user send brain commands to the prosthetic hand, what is usually performed by using electromyographic (EMG) signals (Zecca et al. 2002). In the future, EMG as reference and electric current measured from the motor as feedback signal will be used to control the prehension force delivered by the robotic finger.

## 3. 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 grasp.

$\theta_1$, $\theta_2$ and $\theta_3$ indicate the proximal, middle and distal phalange rotations respectively with respect to the ordinate axis, and $r_1$, $r_2$ and $r_3$ are the pulleys radius of proximal, middle, distal joint. $\theta_m$ and $r_m$ are the driving pulley rotation and radius, respectively.

During the unconstrained motion, $\theta_1 = \theta_m * r_m / r_1$, and $\theta_1 = \theta_2 = \theta_3$. When the phalange i touches the external constrains $\dot{\theta}_i = 0$ and $\theta_{i+1} = \theta_i + \theta_m * r_m / r_{i+1}$; i=1, 2, 3.

Some results from numerical computation have been plotted in Figures 2 and 3, showing first the finger workspace during the unconstrained motion and after the constrained motion.

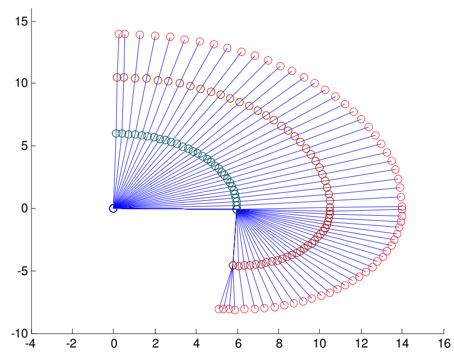


Figure 2. Simulation of the flexion kinematical pattern, unconstrained

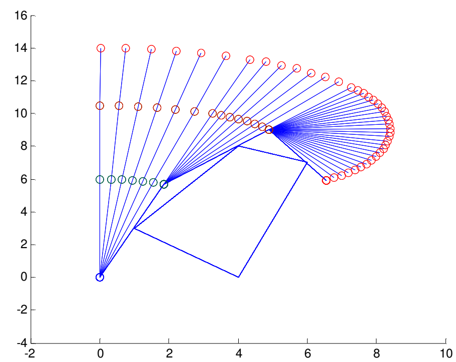


Figure 3. Simulation of the flexion kinematical pattern, constrained

The value of the pulleys radius affects the rotational angles during the closing sequence. So, this tool can be useful to define these parameters in order to mimic the human finger movements.

## 4. EXPERIMENTAL SETUP

To test the mechanism, a finger was build in aluminum, with pulleys machined in polypropylene. The finger has three segments, representing the phalanges of the finger, coupled to the pulleys. Pulleys radius were chosen from proximal to distal as 1.5cm, 1.25cm, 1.0cm, respectively, and no accurate anthropometric dimensions were taken into account to design the device, since the main concern in this stage of the work was to verify the applicability of the mechanism and its actuator.

To study the kinematical behavior of the finger mechanism, an electromagnetic motion tracking system Polhemus Fastrak 3D was used. The system has 1 transmitter (referential) and 4 six degree of freedom position sensors (receivers), and tracks the position (X, Y, and Z Cartesian coordinates) and orientation (azimuth, elevation, and roll) of each sensor as it moves through the space with relation to the transmitter. Each receiver was rigidly attached to each finger's phalange, and the $4^{th}$ to the motor pulley. Figure 4 shows the mechanical device with the position sensors (receivers) installed. Only sagittal plane movements (roll angle) were considered in the analysis (Figure 5).

The captured data by Fastrak were transmitted to computer via an RS-232 serial interface using a Labview Virtual Instrument (VI). The experiments were measured with the motion tracking system at 120Hz (30Hz per sensor).

Motor angle is related to the desired flexion/extension movement. When the angle motor is 180°, the mechanical finger is completely extended. If the angle motor is 0°, the finger reaches the total flexion. By applying a ramp command to the servo, that allows a smooth movement, the flexion and extension unconstrained motion of the fingers phalanges was recorded. In a second experiment, the constrained flexion kinematics was measured restricting the motion of the proximal, distal, and middle phalanges progressively.

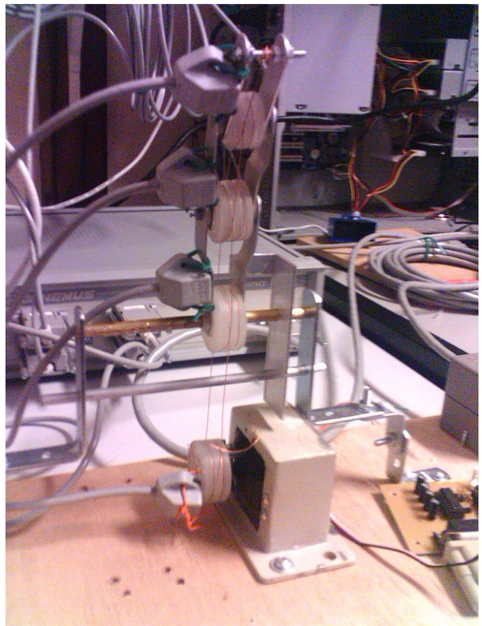

Figure 4. Platform of the mechanical finger

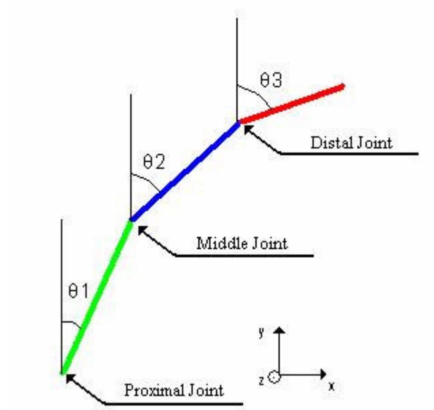


Figure 5. Captured angles during the motion of the finger

**4.1. Actuator driving and characterization**

The Futaba S3003 servo motor was used to drive the finger, and was directly connected to the driving pulley. This specific servo model in very low-cost (about U$25,00/unit), presents a reasonable peak high torque and has low weight. The servomotor is composed by a DC motor, a control circuit and a position sensor (potentiometer) constituting a closed loop system. The control circuit receives a reference signal and compares with the position signal measured by the potentiometer, closing the control loop of position on the motor. The servo-actuator is powered with 5 volts DC and they are controlled by PWM modulation signals. The PWM modulation signals is generated by a low-cost PIC microcontroller, that controls the servo position by a PC RS-232 serial interface, controlled by a Labview Virtual Instrument (VI), developed for this purpose (Figure 6). The period of pulse applied to the command is 50Hz and the width pulse varies about from 1ms to 2 ms, corresponding to angular variation from 0° to 180°. The serial signal carries the desired angular position of the servo, with an overall $3^o$ accuracy.

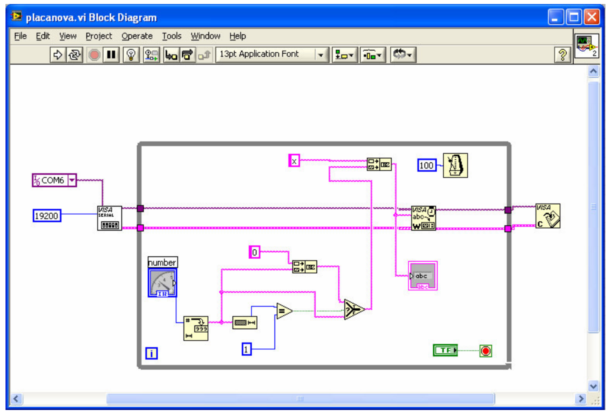


Figure 6. Labview VI for controlling servo

One of the major requirements of a hand prosthesis is to control the prehension force, in order to avoid accidents as object crushing. The prehension force of the finger is transmitted to motor by the tendons (wire). Since the torque of the DC motor is related to its current, this variable was used as the feedback signal. A series of experiments was performed to access some of the actuator characteristics. Different weights, simulating different prehension forces, were attached in the end of a thread and suspended by the servo, using a pulley with known radius (1.5 cm) as viewed in the Figure 7. For each trial, velocity and electric current was measured. To estimate current, a low-value resistor was installed in series with the servo power supply wire, and the voltage recorded by a A/D card.  Table 1 shows the collected data. In Figures 8 and 9 shows the obtained motor curves.

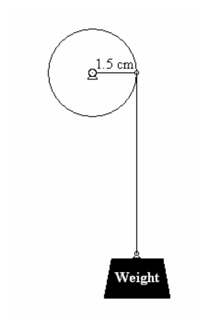


Figure 7. Experiment using different weights

Table 1. Experimental results for average velocity and current for each value torque

| Torque (Kgf.cm) | Average Velocity (rad/s) | Average Current (A) |
|---|---|---|
| 0 | 46.264 | 0.1084 |
| 0.15 | 42.970 | 0.1350 |
| 0.30 | 39.883 | 0.1618 |
| 0.45 | 37.349 | 0.1826 |
| 0.60 | 34.321 | 0.2034 |
| 0.75 | 31.261 | 0.2275 |
| 0.90 | 28.602 | 0.2513 |
| 1.05 | 25.457 | 0.2715 |
| 1.20 | 22.741 | 0.2942 |
| 1.35 | 19.956 | 0.3159 |
| 1.50 | 16.201 | 0.3375 |
| 1.65 | 13.707 | 0.3624 |
| 1.80 | 10.624 | 0.3869 |
| 1.95 | 0.0354 | 0.4489 |
| 2.10 | 0 | 0.4600 |

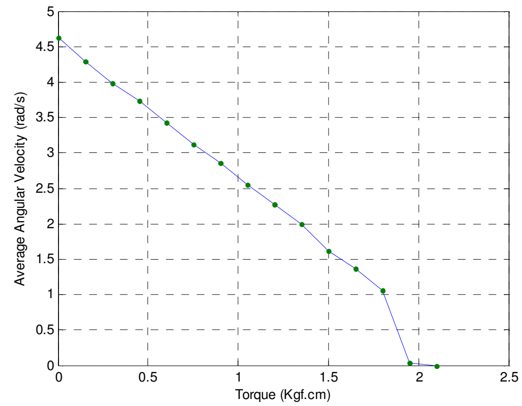


Figure 8. Average angular velocity X Torque

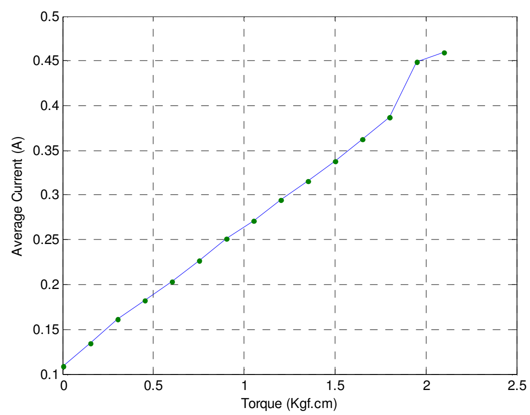


Figure 9. Average current X Torque

## 5. RESULTS

On Figure 10, the phalanges angular displacements during the unconstrained motion are shown. Figures 11, 12 and 13 shows the kinematics of the finger during unconstrained motion, 1 DOF constrain and 2 DOFs constraint, respectively.

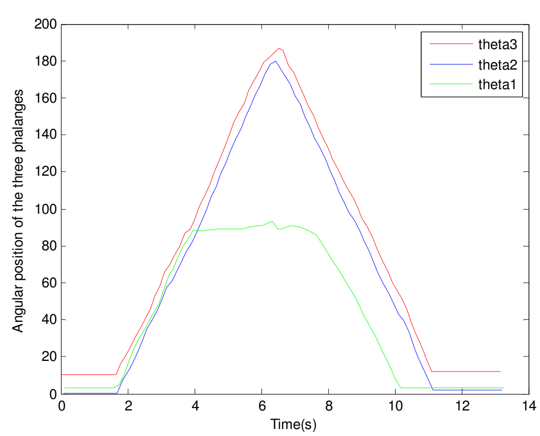


Figure 10. Angular position of the three phalanges during the unconstrained motion of flexion and extension

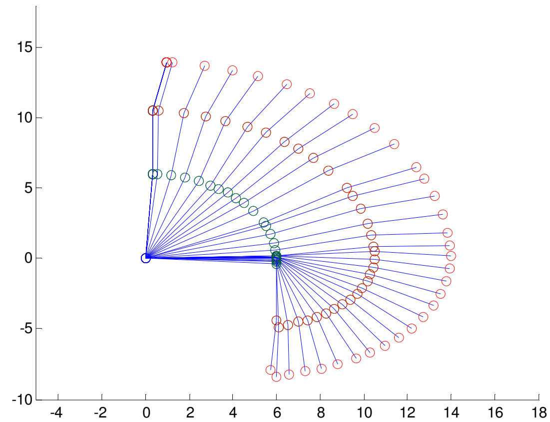


Figure 11. Flexion kinematical pattern, unconstrained

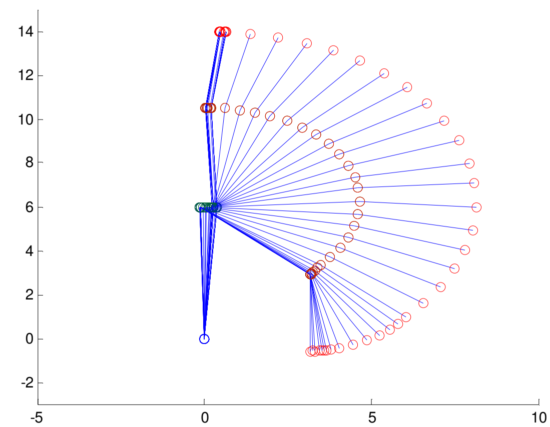


Figure 12. Flexion kinematical pattern for one DOFs constrain

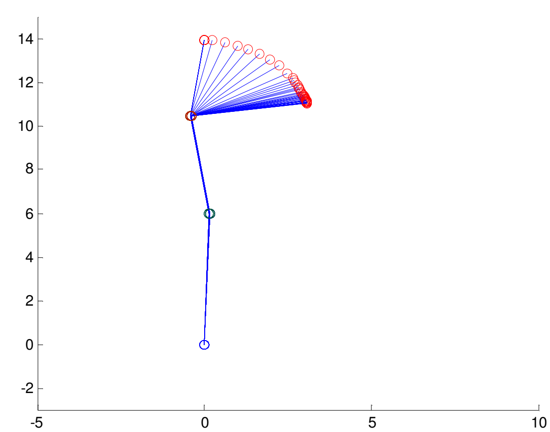


Figure 13. Finger flexion kinematical pattern for two DOFs constrain

## 6. DISCUSSION

The results show that the proposed modification of the finger mechanism, by using two symmetric Hirose mechanisms (Hirose, 1977) is promising. The unconstrained motion apparently differs from natural human finger movement. Here, the finger bends forward extended, and starts to flex only when the 1st phalange reaches its mechanical limit. This behavior should probably be enhanced by a more careful choice of each pulley radius.

However, in the constrained motion, the observed motion suggests that the mechanism is capable of adapting itself to the shape of the touched or grasped object, once phalanges bend themselves in sequential way when their movement is constrained. At the same time, it was observed that the finger returns to the initial position after total extension, regardless of the previous motion history. This indicates that the proposed mechanism modification is effective for extension, without using torque-draining elastic elements.

Future works will be focused in the design of the finger with anthropomorphic features and the development of a closed loop grasp force controller, using real time measured electromyographic signals.

## 7. ACKNOWLEDGEMENTS

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