Design of an Anthropomorphic Underactuated Hand Prosthesis with Passive-Adaptive Grasping Capabilities

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ABSTRACT
This paper presents the design and mechanical features of a functional self-adaptive, multi-fingered prosthetic hand that improves upon current prosthetic hands. Commercially available hand prostheses, though functional, have limitations such as weight, as result of vast numbers of parts, intricate mechanisms requiring constant maintenance as well as the extremely high cost to the user. The hands design discussed is based on an underactuated 15 degree-of-freedom, 1-degree-of-actuation configuration, fully capable of performing activities of daily living. Each finger is fully independent from each other and is designed to adapt to objects of any geometry while possessing the ability of pick up smaller objects through pinching, by means of a position adjustable thumb. The system provides safe and reliable grasping without the need for feed back sensors, multiple servos, or any type of data processing. The design is focused towards providing upper limb amputees with the option of a prosthetic hand that is cosmetically appealing, functionally comparable with other prosthesis of its type, while decreases cost and weight issues by using an approach that eliminates the need for complex electrical systems, circuitry, and multiple servomotors while decreasing the number of parts and cost of manufacturing.

Keywords  
Hand Prosthesis, Underactuated, Self-adaptive, upper-limb amputees

1. INTRODUCTION
For the past decade or so, there has been an increased interest in the design of functionally and cosmetically anthropomorphic robotic end-effectors. The technology and expertise has crossed over into, and benefited the area of prosthetic hand design [6]. Unfortunately, this type of technology is expensive and generally inaccessible to those without insurance or monetary means in developed countries and almost completely inaccessible to most in developing countries. At the most general level, upper-limb prostheses are actuated by means of body or external power, with a hook or hand-shaped end-effectors. In the United States, approximately 70 percent of upper-limb prosthesis users wear hooks [7]. In most other parts of the world, especially in developing countries, human hand-like prostheses are the most commonly preferred. Compared to hooks, prosthetic hands generally offer less function and durability at greater weight and cost [9]. Nonetheless, many individuals still choose hands over hooks, primarily for cosmetic reasons. The design being put forth by this paper describes a highly functional prosthesis that decreases overall weight and costs through the use of a simplified system consisting of a signal motor controlling all five fingers, with each finger being passively adaptive [9].

2. PROSTHETICS BACKGROUND
There are a wide variety of prosthetic devices available for upper-limb amputees ranging from those that are mostly cosmetic on one end, to those with functionality in mind on the other end. In general, most prostheses are designed with both extremes in mind [1]. Though cosmetic prostheses offer a more natural look and feel, they sacrifice functionality and versatility while also being relatively expensive. Active prostheses can be divided into two general categories: body-powered prosthesis, and myo-electric prosthesis.

2.1 BODY POWERED PROSTHESIS
Body-powered prostheses are powered and controlled by gross movements of the shoulder, upper arm, or chest and are captured by a harness system which is attached to a cable that is connected to a terminal device (hook or hand) [1]. They tend to be of moderate cost and weight while being very durable at the sacrifice of esthetics.

Figure 1. Body-Powered Prosthesis

2.2 ELECTRIC POWERED PROSTHESIS
These types of prostheses use small electrical motors found in the terminal device (hand or hook), wrist, and elbow [1]. Electrical activity transmitted from the residual limb to the surface electrodes on the prosthetic fitting control the different motors by means of a microprocessor unit. For the most part, these are pinched type devices consisting of a pair of rigid fingers in opposition to a rigid thumb which are limited to a single degree of freedom; that is an open or close. These types of prosthesis are sometimes covered by a hand like glove providing greater proximal function and increased cosmetic appeal (often at the
expense of efficiency), but also tend to be much heavier and more expansive than any other types of prosthetic devices available.

Figure 2  Myo-electric hand with hand-like glove covering

2.3 RECENT ADVANCEMENTS
Over the past several years trends in prosthetic hand research have dictated a move away from grippers having only two rigid fingers and no phalanges, focusing more on hands with at least three to five functional fingers, each with two to three phalanges [2]. Several types of electric powered hand prosthesis with four functional fingers and a thumb have been created in an attempt to increase user acceptance and satisfaction. Two examples of these advanced types of the hand prostheses are the Montreal and Southampton hands, which rely on innovative mechanisms or myo-electric control systems.

The Montreal hand is an adult sized anthropomorphic hand with passive adaptive capabilities achieved by means of a clutch, a cable system, and a spring-loaded pulley mechanism [6]. Like the Montreal hand, the Southampton hand prosthesis is also a five-fingered adaptive system. In this case, grasping is performed through computer control of the fingers by means of multiple motors and sensory feedback [6]. In both cases, the prosthesis offers more human-like finger function, though not without its drawbacks. Results from testing of the Montreal hand showed significant problems with the cable system design in terms of reliability, whereas the Southampton hand had issues associated with overall size, weight, and cost as a result of the increased number of motors as well as the more advanced technologies associated with the controls system.

2.4 USER PREFERENCES
Essential to the design of prosthetic limbs is the inclusion of user feedback and suggestions in order to minimize the risks of user rejection of the prosthesis in the long term. Recent surveys have shown that the following five items are considered most important for those interested in or using active prosthetic hands [9]:

1. Prostheses should be able to grasp both small and large objects properly and securely
2. Thumb should have the capability to be repositioned for different grasping or pinching configurations
3. Fingers should have active joints
4. Prosthesis should be low in weight
5. Cosmetically appealing

It was our intent with this prosthetic hand to implement all of these user points of interests into our design.

3. DESIGN PARAMETERS
The design parameters were chosen based on identified needs of prosthetic hand users and the desired features involving functional underactuated fingers and thumbs [3]. The following is a list of the seven main design parameters that were chosen for use in the design process:

1. The prosthetic hand must be made up of five, three degree of freedom digits.
2. Fingers will be control by a single actuator
3. Fingers must passively conform to objects of different sizes and shapes
4. It must be engineered so as to allow each of the five hand digits to be actuated by a single input, while allowing each to operate independently with respect to the rest.
5. Must perform gross grasping operations as well as pinch an object between the thumb and index finger, thumb and middle finger, or a combination of both.
6. Cosmetic appeal
7. Lightweight
8. Cost-effective and easy to manufacture

4. DESIGN METHODOLOGY
In order for the previously described parameters to be met, specially designed mechanisms where adapted and/or modified for the hand prostheses. A specifically arranged and designed differential system allowing for independent motion between all fingers using planetary gear systems was used. These planetary systems were connected to lead screws, which translated rotational motion to linear translation in order to actuate the specially designed 7-degree-of-freedom fingers. The thumb was actuated using a pulley system in response to the fact that its plane of motion is adjustable for different pinch configurations.

Figure 3. (1) Multi-linked fingers, (2) Thumb, (3) Lead screw and nut, (4) Planetary Systems, (5) Thumb Pivot, (6) Palm plate, (7) Thumb/Wrist section, (8) Motor, (9) Pulley system

Figure 3 in the previous page shows the main parts that comprise the prosthesis hand design and in the following sections each of these systems or mechanisms will be described in detail.
4.1 Differential system

For all five fingers to work independently of each other, a differential mechanism based on the coupled, coaxial planetary gear system design for the end-effector robotic hand being developed by the University of Laval in Canada, to be used in the Canada space arm, was designed [5].

![Figure 4. University of Laval End-Effector using coupled planetary system](image1)

In the case our prosthetic hand, a four coplanar-two coaxial planetary gear system was used. Adjacent coplanar systems where coupled together through the use of an adapted planet carrier gear mated with the adjacent ring gear. The coaxial planetary systems were coupled together using a specially designed sun gear to planet carrier piece.

![Figure 5. (Left) Carrier gear (Right) Sun-to-carrier piece](image2)

A single motor was used to produce the torque necessary to actuate the mechanism. This motor is connected to the index finger through the coplanar planetary systems and will stop rotating only as a result of all five fingers having reached their limiting positions. As figure 6 (side view) shows, the planetary systems on the index figure transmits motion to the thumb by means of two gears coupled to the index ring gear, and then through a shaft with a cabled pulley actuating the thumb. The only finger not directly attached to a planetary system is the fifth metacarpal (pinkie finger; No. 9), which is driven by a single gear coupled to the ring gear of the fourth metacarpal.

![Figure 6. Exploded view of planetary gear differential system](image3)

Figure 6 shows the planetary systems driving each of the four fingers (index finger on the left and pinkie finger on the far right). The fully exploded planetary system on the left drives the index finger and marked from two to four are the ring, sun, and planet gears respectively. Items one and five are the planet carriers with part five being the carrier gear with three shafts mating onto the female planet carrier (No. 2). In order to maintain the structural integrity of each planetary system, the planet carrier's inner and outer diameters were made small and larger respectively, with the sun gear anchoring the system to the respective finger's lead screw. Adjacent to the index planetary system are the two coaxial planetary systems, which are coupled through the sun-to-carrier piece (No. 8). Input from motor is received from the drive flange, which attaches to the shaft of the motor (No. 7) and is transmitted to the lower planetary system through a planet carrier, which is fixed to the drive phalanges by means of three screws. The figure shows how the sun-to-carrier piece transmits motion to the upper planetary system on the middle finger through the planet carrier, causing the sun gear, attached lead screw and ring gear to rotate in the opposite directions, independently. This is the case for all four planetary systems; input torque enters through the planet carrier and exit through the sun and ring gears independently. This will continue to happen while all fingers have not yet reached their limiting positions. Once this occurs, relative motion between gears will cease to occur and all fingers stop moving as a result of having fully conformed to the object being grasped or reaching a limiting positions. Figure 7 below shows how the motor’s input torque is distributed through the system as well as the relationship between input (motor) and output (lead screw) $\omega$.

![Figure 7. Torque flow through planetary systems and shafts](image4)
Given that energy follows the path of least resistance, applying small amounts of friction to the shaft (lead screws) will allow for the manipulation of the order in which each finger will close with respect to the others.

### 4.2 Lead Screws

The sun gear is attached rigidly to self-locking lead screw shafts which converts rotary motion into linear motion to the screw mount (driving nut) connected to one of the four fingers by means of a driving link (the thumb is actuated using a pulley mechanism discussed at the end of the section). A self locking lead screw is one where the lead angle is less than five degrees and thus prevents back driving of the nut when external forces, such as the weight of the object being picked up, act on the fingers. This is very important since it prevents the need for the motor to continually apply torque to the fingers once the fingers have fully adapted to the object.

![Figure 8. Lead screw setup](image)

The figure above shows how lead screws are set up on each finger. The lead screw shaft is mounted on low friction ball bearings set on a specially designed mount on the palm. As input from the planet carrier causes the sun gear to move, the lead screw will rotate accordingly with the nut translating rotary motion into linear motion, causing the finger-driving link to begin rotating by means of the nut-to-finger coupling link. Each lead screw has a right or left-handed threading, depending on the corresponding direction rotation of the sun gear so as to allow each finger to flex in the proper direction. Based on simple conventions, the index and pinkie lead screws are left-handed while the middle and ring finger lead screw have a right handed threading (fig.7)

### 4.3 Fingers

The hand’s ability to adapt to different shapes and objects required fingers with the capacity to be self-adaptable without the need for external power or control. This necessity was met by using a seven-bar mechanism for each finger. In order for the fingers to function in similar fashion to that of human finger, it was designed using three different sections (distal, medial, and proximal). The axis of rotation for the proximal link will be referred to as the metacarpal-phalangial joint (MCP), the axis of rotation of the medial link is referred to as the proximal interphalangial joint (PIP), and the axis of rotation of the distal link will be referred to as the distal inter-phalangial (DIP). Figure 9 highlights these different features of the fingers.

![Figure 9. Finger design](image)

The proximal and medial sections are composed of four-bar mechanisms couple to each other at the PIP joint, while the distal section of the finger is represented by using a tertiary link at the end of the medial four bar mechanism. The figure below shows how the finger behaves as each section comes in contacts (and stops).

![Figure 10. Finger Configurations: (a) No external force, (b) proximal link external force, (c) Proximal & Medial external forces](image)

Initially, the finger behaves as one single tertiary link actuated at the MCP joint of the proximal link. The ability of each link to maintain its position relative to the others while no external forces are applied is achieved through the application of an opposing torque at the joints, in this case achieved through the introduction of small frictional forces, at the axis of rotation of the medial and distal links. To achieve this, the fit between each link was designed to be flush so as to create just enough fictional forces at these points. In the case where more friction was needed, C-rings were placed at the connecting shaft’s bolt head. As each link comes into contact with the object, it shifts from behaving as a simple tertiary link, to a four-bar mechanism (composed of three binary and one tertiary link), and finally to a seven-bar mechanism.

In order to prevent hyperextension at any of the joints when they hand is opening, it was necessary to place mechanical limiters composed of a shaft on one link and a hook on the adjacent link.

![Figure 11. See-through view of a finger between the medial and distal axis of rotation](image)

As figure 11 shows, as the hand extends open the links rotate counterclockwise. Hyperextension is prevented by the use of hook-like sections at the ends of the distal and medial sections.
which lock into the corresponding pin shaft when maximum extension is achieved. In the case of the PIP joint, the limiting angle is 20 degrees, were at the distal it is 0 degrees. The dimensions and proportions used in the design were obtained from average population data. The nominal values for the palm, hand, finger lengths as well as the hand breadth were used and the standard deviation added on to this value. The reason for adding the standard deviation to the nominal value was very basic. Due to the use of planetary systems, it was necessary to make the hand as large as possible while still stay within portion of what is considered a human hand so that the planetary gears would comply with design specifications and needs. Fingers link lengths were calculated using the “Golden Section” rule, as shown by the calculations below.

\[
\text{Finger Phalange Lengths:} \\
\text{Distal Phalange Length} = x \\
\text{Golden Proportion} = 1.61803 \\
x \times 1.61803 = 1.61803^2 = 3.62 \\text{solve for } x \\
\rightarrow x = 0.69136071135841084266 \\
\text{Distal} = 0.69 \\
1.116 \\
\text{Medial} = 1.12 \\
1.812 \\
\text{Proximal} = 1.82 \\
\]

Figure 12. Calculation of finger link lengths

4.4 Thumb design

The actuation of the thumb is of greater complexity than that of the fingers due to the design parameters, though both are exactly the same in portion and general link design. First, the MCP joint is required to have two degrees-of-freedom as opposed to the fingers that only have one degree-of-freedom MCP joints. This feature stems from the design parameter requiring a variety of pinching configurations between the index, middle finger, and the thumb. Second, because the thumb has multiple degrees of freedom, actuation by means of a lead screw was not feasible. It was then decided that a cable and pulley system was the best suited mechanism to use since it would allow the thumb to rotate into several pinch positions while maintaining the capability to actuate. The pulley system was designed to actuate the thumb utilizing input torque from the ring gear of the index finger’s planetary systems on the top half of the palm.

Figure 13. Pulley/Cabling system setup for thumb actuation

Figure 13 shows how a gear mounted at the base of the plot is used to couple the ring gear of the index finger planetary system with a pinion gear below the palm. The pinion gear is rigidly attached to a shaft at its axis of rotation, which is also connected at the other end to the main cable pulley. From the drive pulley, a line is fed through a cable, which runs from the pulley inside the palm up to the thumb pulleys. The line then runs through two small pulleys placed in the middle of the proximal figure by means of a small shaft fixed to each side of the links and attached to the driving link in the proximal four-bar mechanism. This allows the thumb to rotate about the MCP joint and close on an object in a similar fashion as the other fingers. In order for the thumb to retract when the hand opens, a tension spring was attached between the thumb’s driving link and to the thumb's pivot joint as seen in the figure below.

Figure 14. Thumb extension spring system

Changing pinching configurations is a simple process and is done manually by the user. The thumb MCP pivot joint is held in place by means of a spring-loaded axial screw, which attaches to the hand’s palm. Spring loading the screw against the palm causes the pivot to be held in place by means an upward force and friction. Changing a position simply implies rotating the thumb pivot with a certain amount of force. A guide shaft runs through a path on the palm which limits the range of motion to 35 degrees.

Figure 15. Thumb Pivoting Mechanism

4.5 Increasing grasping/ pinching capabilities

Given the limited contact area between fingers and small object in pinching configurations, it is often difficult to secure the object in place when lifting or moving without having to increase the surface contact area or force. In order to minimize this effect all of the finger links are covered at the bottom end plates with a special material called Dycem®.

Dycem® is a specially design polymer material with an extremely high coefficient of friction several times larger than that of the human skin. This material is available in the thin, smooth sheets making it simple to manipulate, cut, and adhered to each section
of the palm, fingers link plates, fingertips, and thumb links as shown in the figure below.

![Figure 16. Contact surfaces covered with high friction polymer](image)

4.6 EXTERNAL GLOVE
In order to improve the cosmetic appeal of the prosthetic hand, an external silicone glove would be used to cover the robotic hands exoskeleton. The prosthesis design includes a palm top covering (See figure 17) in order to protect the different mechanisms from coming into contact and interfering with the glove, which also serves as a protective cover for the vulnerable hand mechanisms.

5. DESIGN MODEL AND ANALYSIS
The initial model concept and final design was created using SolidWorks® CAD software. Based on this and an initial model using the SolidWork’s motion analysis software add-on, CosmosMotion®, kinematic analysis, range of motion, contact forces, angular accelerations, and velocities were calculated. The calculations were obtained by creating an exact stimulation of the design including every single mechanism along with the exact specifications such as pitch diameters, lead screw threading pitch and lead angles.

6. MANUFACTURING AND COST
The final design has a total of 93 components (not including fasteners) derived from 28 key parts. A key part is defined as one which has a single or more duplicates (i.e. planet gears and finger segments). All finger and thumb components are the same with the exception of the proximal section of the thumb. Most key components of the different planetary gear systems are identical and the gear specifications chosen are standard, making manufacturing of the gears more cost effective. In general, the fact that there are relatively few parts in comparison to commercial electric-driven hand prosthetics inherently lowers the cost of production. Furthermore, the relative simplicity of the parts designed along with the use of stock items such as the lead screws, nuts, and ball bearings will reduce production cost even more. Considering that the cost of a myo-electric hands ranges from $14,000 to $70,000 [7], the savings past on to the end user could be significant.

Currently, a prototype is being created with 90% of the parts being created using a stereo lithography apparatus (SLA). Including the motor, lead screws, ball bearings, and fasteners, all of which are stock items and relatively inexpensive, total cost of manufacturing is estimated at around $1,100. Ultimately, by using more cost effective manufacturing processes to create the parts being made using SLA rapid prototyping, which is a relatively expensive process, total cost of production could be well bellow the $1,000 level.

7. DISCUSSION
Ultimately, this design will provide a cheaper, less complex, lighter, and more easily manufacturable hand prosthetic device. Its functionality and anthropomorphic design will make it more acceptable to amputees who have a hard time adapting to prosthetic devices use. Moreover, the fact that all five fingers, planetary gears systems, and lead screws and nuts are identical, means manufacturing costs would be substantially lower than that of myo-electric prosthetics, which contain expensive servo's and electronics. This would make functional prosthetic devices accessible to people with limited resources not only in the U.S. but also Third World countries, where resources are extremely limited to those most commonly afflicted with these types of injuries.

![Figure 17. Hand in grasping mode](image)

8. REFERENCES


