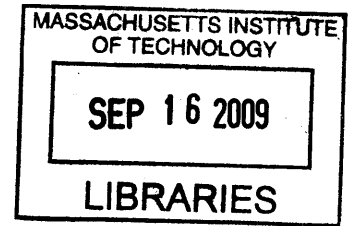


INTER-FINGERCOORDINATED DC MOTOR DRIVEN
GRASPING ROBOTIC HAND

by

Sarah Jane Wikman



Submitted to the Department of Mechanical Engineering in
Partial Fulfillment of the Requirements for the Degree of

Bachelor of Science

at the

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ABSTRACT

Many robotic hands have individually driven joints, which is both energy inefficient and complicated to control. An alternative method includes employing only one motor to control multiple joints. Investigating humanoid hand movements used in everyday tasks, graduate students working with Professor Asada discovered through Principal Component Analysis that a majority of these motions can be approximated by a grasping motion. Implementing PCA results on a humanoid robotic hand yields an inter-finger coordinated motion in which each of the four fingers closes towards the palm and each individual joint's velocity is linearly proportional to the others. The coordination is achieved through a system of pulleys with different radii. The cables used in conjunction with these pulleys, emulating tendons, will be driven by a DC motor for simple control of a complex hand mechanism. The thumb is excluded from this system as it functions differently from the remaining digits.

Thesis Advisor: H. Harry Asada

Title: Ford Professor of Mechanical Engineering

Biographical Note

Sarah Wikman was born in Rockville Maryland and attended Poolesville High School from 2001-2005. She was a student in the Massachusetts Institute of Technology Department of Mechanical Engineering from 2005-2009.

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1. Introduction

As robots become a larger part of daily life, they serve a greater variety of functions. Additions to the field of robotics include home helping robots and prosthetic limbs. Home helping robots would be made more efficient with the use of more articulate manipulation, as would greater agility in prosthetic hands benefit amputees in returning to a fully functional lifestyle. Various hand-manipulators for these purposes are often bulky and energy inefficient due to a large number of actuators applied to the vast degrees of motion in a human hand. Others are simplified to avoid these problems, but reduce the deftness of the hand-manipulator.

One concept that has not been fully utilized in humanoid hand manipulators is inter-finger coordination. The methods presented in this paper employ this technique in an attempt to realize the most prominent postures seen in frequently observed hand positions. Inter-finger coordination is a principle derived from the biological layout of the human hand and from muscle memory. Tendons and muscles do not have a one to one correlation, and influence and partially control multiple fingers. This coupling causes a human hand to consistently assume postures along certain position axes. These positions can be determined by a method known as Principal Components Analysis.

1.1 Related Works

The primary two goals of robotic hands to date have been prosthetic replacements and remote manipulation. Until recently, these robotic “hands” typically consisted of three digit grippers. Manipulation was handled by the robot arm, or human’s arm to which the robot was attached, instead of the fingers themselves. Multi-fingered robotic hands have the advantage of being capable of grasping various shapes with more points of contact leading to more stability [1]. They can also manipulate objects with the fingers because of these extra digits. The methods

presented in this paper do not explore further motions, but may in the future be extended to these purposes.

Various attempts at more functional hands have been constructed. One extensive hand was produced by Okada in 1979. Despite having only 3 fingers, the robot contained 11 joints and needed to be controlled by a computer [2]. This proves that for a hand with more digits and an actuator for each joint, it would be very difficult to control each joint individually. Brown [3] and Rosmarin [4] have constructed similar inter-finger coordinated hands actuated by two stepper motors and a combination DC motor-SMA actuator system, respectively.

1.2 Scope

The methods presented in this paper were developed in an attempt to solve weight and control issues present in previous grasping hand designs. The proposed strategy involves reducing the number of actuators to eliminate these problems. The robot hand will be of humanoid design to aid in integration into, for example, an amputee's daily life. All finger joints will be controlled remotely by a single DC motor located below the palm. Employing a single actuator results in each finger becoming incapable of individual motion. Therefore, the hand is utilizable only under circumstances in which the fingers undergo similar movements.

2. Inter-Finger Coordination

One concept that has not been fully utilized in humanoid hand manipulators is inter-finger coordination. The methods presented in this paper employ this technique in an attempt to realize the most prominent postures seen in frequently observed hand positions. Inter-finger coordination is a principle derived from the biological layout of the human hand and from muscle memory. Tendons and muscles do not have a one to one correlation, and influence and partially control

multiple fingers. This coupling causes a human hand to consistently assume postures along certain position axes. These positions can be determined by a method known as Principal Components Analysis.

2.1 The Human Hand

The fingers of the human hand are controlled by a complex system of muscles and tendons. Tendons that run through and control the fingers are connected to and driven by muscles in the hand and forearm. Extension and flexion of the fingers are controlled by opposing groups of tissue. The muscles that extend the fingers are located in the forearm and long tendons connect them to the finger joints being controlled. Flexion is controlled by tissues in the palm. Figure 1 shows the muscles and tendons on the back of the hand, the extensors. The figure clearly shows that the correlation between the tendons and fingers is not one to one.

These tendons and muscles interwoven across multiple fingers cause biomechanical constraints. These constraints are partially responsible for inter-finger coordination [3]. When the brain signals a finger to move, any tendon connected to both the activated finger and a separate one will also have an effect on the finger not being actively controlled by the brain.

The other factor that contributes to inter-finger coordination is muscle memory. Certain hand postures are much more common in daily life than others, and the brain becomes accustomed to firing neurons to elicit these positions. Postures that would be subtly different from these repeated positions will be influenced by and begin to approximate the more prominent positions. The frequently repeated hand postures and inter-finger coordination that result from the biomechanical constraints and brain induced muscle memory can be analyzed with Principal Components Analysis.

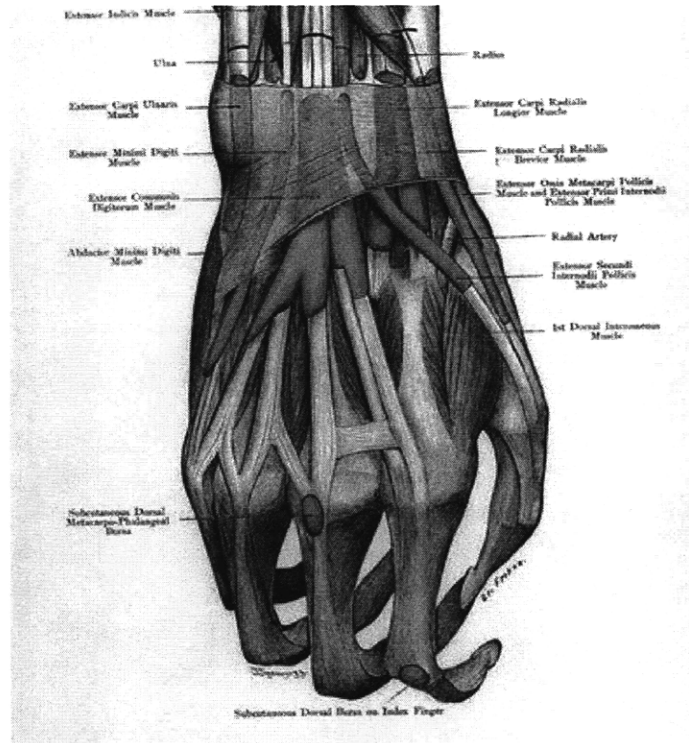


Figure 1: Muscles and tendons on the back side of a human hand. Notice that on each finger, multiple tendons connect to each finger, and a single tendon may split to connect to multiple fingers. This phenomenon plays a part in inter-finger coordination.

2.2 Principal Components Analysis

Principal Components Analysis, hereafter referred to as PCA, can be summarized as a sort of data compression method. Consider a matrix \mathbf{P} which contains values representing any form of data. The number of columns in \mathbf{P} is the number of dimensions in the data set and the number of rows is the number of data points. The first step of PCA is to take the covariance matrix of \mathbf{P} .

Covariance is defined as

$$\text{cov}(X, Y) = \frac{\sum_{i=1}^n [(X_i - X_{\text{mean}})(Y_i - Y_{\text{mean}})]}{(n - 1)} \quad (1)$$

and the covariance matrix is

$$\mathbf{C}^{m \times n} = (c_{i,j}, c_{i,j} = \text{cov}(\text{Dim}_i, \text{Dim}_j)) \quad (2)$$

This yields a square matrix of $n \times n$, where n is the number of dimensions in the data set. Each entry in the covariance matrix will be the covariance of two separate dimensions of the data set. Then calculate the eigenvectors and eigenvalues of the covariance matrix. The eigenvectors are the principal components of the data set and show the trends of how the data are related. The respective eigenvalues rank their prominence of each of these trends. Thus, a higher eigenvalue dictates a stronger trend in the data along its eigenvector.

Figure 2 shows a set of data with two axes of freedom. From this figure, we can visualize a simplified version of PCA. In order to decrease the amount information needed to convey the data, we can represent it along one axis instead of two. Employing statistics, a slope can be chosen to minimize the variance among the data set. This new axis has the same slope as the eigenvector. Each data point can then be projected onto the new axis and approximated by a single value. This concept can be extended to data sets with greater numbers of axes.

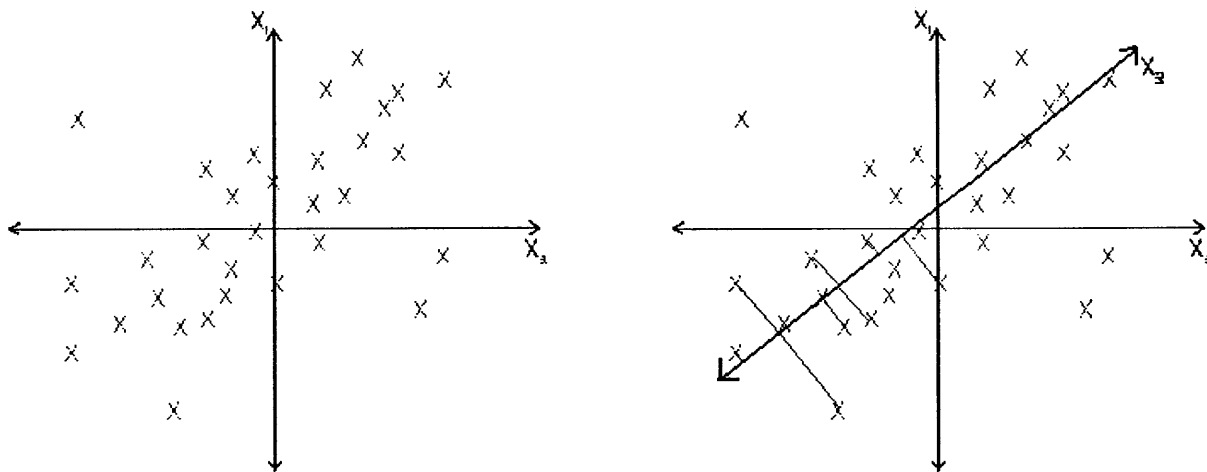


Figure 2: A new axis formed by an eigenvector can be used to decrease the number of coordinates to describe each data point. This can be extended to a greater number of axes. The new, reduced number of coordinates will lose some of the original information, but if the new axes are accurate enough, the greater simplicity can be a valuable factor in controlling a system.

2.3 Application of PCA to Hand Design

If PCA were to be used on hand postures mentioned in section 2.1, each piece would be as follows. The matrix \mathbf{P} contains a data set of hand positions defined by, for example, the angle of each finger joint. The number of finger joints is the dimension of the data set. The eigenvectors of the covariance matrix are the series of motions of the hand along a certain posture set. Brown [3] names these eigenpostures. The eigenvalues of these are the prominence of the eigenpostures seen in the collected data set.

Validly employing PCA requires that the initial data set contain reasonable trends. In the case of the human hand, inter-finger coordination and frequent hand postures make implementing PCA a suitable strategy for constructing a mechanical approximation. Using a special data glove to collect hand postures seen frequently in daily tasks, Rosmarin [4] found that the principal hand posture vector accounted for 68% of the data. It can be concluded that this posture axis, a grasping motion, is a dominant set of positions and that achieving this range of motion would be a practical goal to set for a robotic hand meant to be useful in a daily life setting.

3. Design and Implementation

3.1 Serial Linkage Robotics

Many robots function through the use of serial linkages. The two types of joints typically seen are prismatic and revolute joints. Prismatic joints are not relevant to this paper, and thus only revolute joints will be discussed. Figure 3 shows an example of a 2-bar linkage system. The first joint is pinned to ground, and the second joint is pinned to the free end of the first joint. The coordinates (x_e, y_e) depict the end of link 2 which is typically the location of the robot's interface to

its environment, known as the end effector. These coordinates, while defining the position of the end effector which is often the relevant concern, do not fully define the position of the rest of the robot. Therefore, the coordinates θ_1 and θ_2 are often used to describe the position of the robot. Coordinates fully defining a system are known as generalized coordinates. In this case, if the lengths of both linkages l_1 and l_2 are known, the coordinates of the end effector (x_e, y_e) can be determined through kinematic equations.

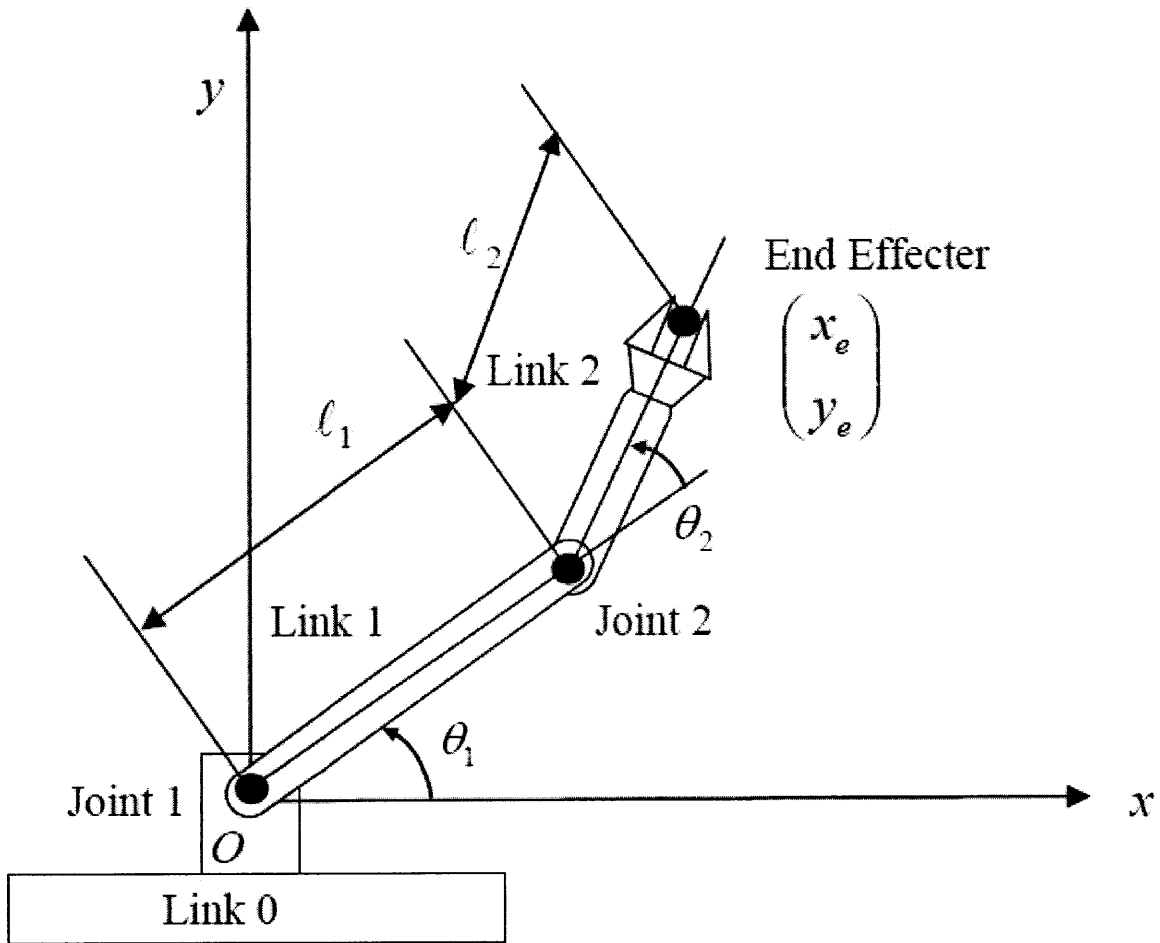


Figure 3: A two bar linkage robot with end effector at (x_e, y_e) . If the lengths l_1 and l_2 , and the angles θ_1 and θ_2 are known, the position of the end effector can be determined by these values through kinematic equations.

3.2 Application of Serial Linkage Robotics

Each finger stemming from the hand can be modeled as a 3-bar linkage system stemming from a fixed point. Figure 4 shows a schematic of this model. The entire finger interacts with the environment, as the entire surface of the ventral part of the finger can be placed in contact with an object during a grasping motion. Since the objective of the robotic hand is to control the position of the entire finger, and not solely the finger tip/end effector coordinates (x_e, y_e) , the relevant parameters to be considered are the angles θ_1 , θ_2 , and θ_3 . However, the actuators for

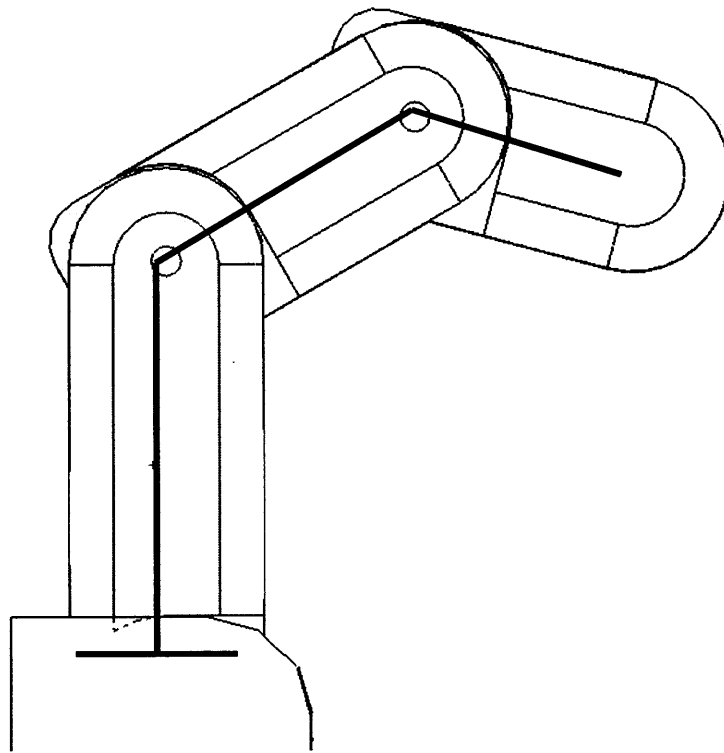


Figure 4: A finger is a 3-bar linkage structure where link 0 is the hand.

these angles are not located at the joints themselves. Actuators located at the joints adds weight to the system, causing actuators to exert more force or torque which leads to less than optimal efficiency.

3.3 Cable and Pulley Driven Actuation

The control method for this robotic hand uses cables fixed at each joint which are connected to an actuator beneath the hand. The control cable for each finger segment is threaded through the hollow spaces in each subsequent finger segment and down through the hand itself. All the cables are connected to a single shaft which is driven by a DC motor.

The values θ_1 , θ_2 , and θ_3 are remotely driven, so they must be determined by some other variables. Figure 5 shows a simplified representation of the cable running from the finger segment to a pulley on the control shaft. This figure demonstrates the importance of the relationship shown in equation 3.

$$s = r \theta \quad (3)$$

The value r is the radius of a pulley embedded in the finger segment. θ is the change in angle the pulley rotates through. The cable attached to the pulley must displace by a linear distance s to rotate the pulley. The other end of the cable is attached to another pulley on the control shaft. If

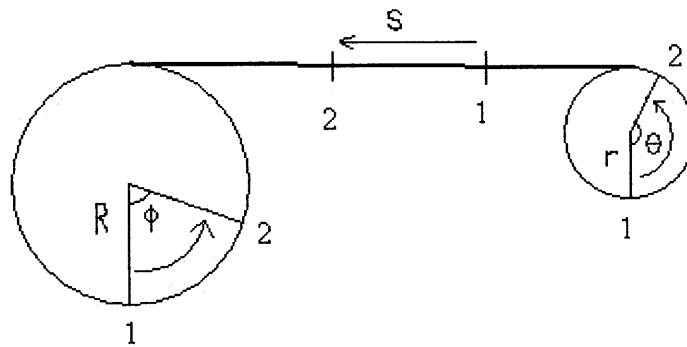


Figure 5: As the smaller pulley rotates from state 1 to state 2, the cable wrapped around it must displace by distance s . If the cable is to stay in tension, the larger pulley must also rotate to take up the slack of the cable. These relationships are defined in equations 3 and 4.

the cable must displace by s , equation 3 applies for the second pulley's radius R and its angle ϕ .

Therefore

$$r \theta = R \varphi \quad (4)$$

The angles through which each finger joint displaces vary by over 40° . If each finger joint contains the same internal radius, either φ or R must differ in order to achieve the correct change in angle. Since all the tendon cables are being driven by the same shaft, φ cannot vary. This means that R must be different for each different θ . Hence the various pulley sizes implemented in this design. Figure 6 shows the various pulley sizes on the shaft. Each joint closes at a linear angular velocity that is in turn linearly proportional to each other joint's velocity. In a real human hand, the joint velocities of a grasping motion are nonlinear. This fact is not relevant to this model, but if a more accurate representation were to be constructed, the nonlinearity could be accounted for with irregular, oblong pulleys, which would change R over the shaft's rotation φ .

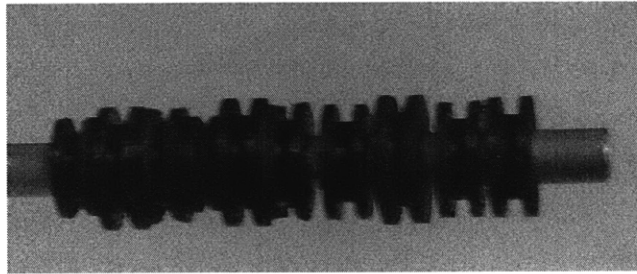


Figure 6: Pulleys to control fingers of the hand. Different sizes are meant to control various angular velocities

The cables controlling the finger segments represent the tendons in a human hand. The tendons driving each finger are then connected to a motor which could represent a muscle. In this case, the motor represents the flexure muscles situated and a set of springs embedded in the hand represent the extensor muscles. The method of driving all the finger joints with one motor is the implementation of inter-finger coordination. Were one finger to displace, all other fingers would displace as well. This is, of course, an over-simplification of the biologically observed

phenomenon, but for the purposes of the movements desired from this robot it is a valid approximation.

3.4 Prototype

The finger segments and hand base were solid modeled and, using those models, printed in plastic on a 3d printing machine. This manufacturing process eliminates the complicated machining tasks that would be necessary to achieve such detailed and irregular geometries seen in the prototype. The cables are Kevlar for durability. Figure 7 shows the assembled hand. With the correct geometry, a flesh-like gel could be molded in the likeness of a human hand and attached to the skeletal robotic assembly to create a more realistic prototype.

4. Conclusion

The objective of this robotic hand is to achieve an easily controllable and energy efficient system incorporating a majority of movements seen in daily life. Previous works in the field of robotic graspers are typically too bulky to be used in practical applications. By observing human hand postures and analyzing the data with PCA, researchers concluded that a large percentage of hand positions can be approximated by a simple grasping motion. Taking human hand tissue structure into account, this motion has been reconstructed using a system of pulleys and cables driven by a single DC motor.

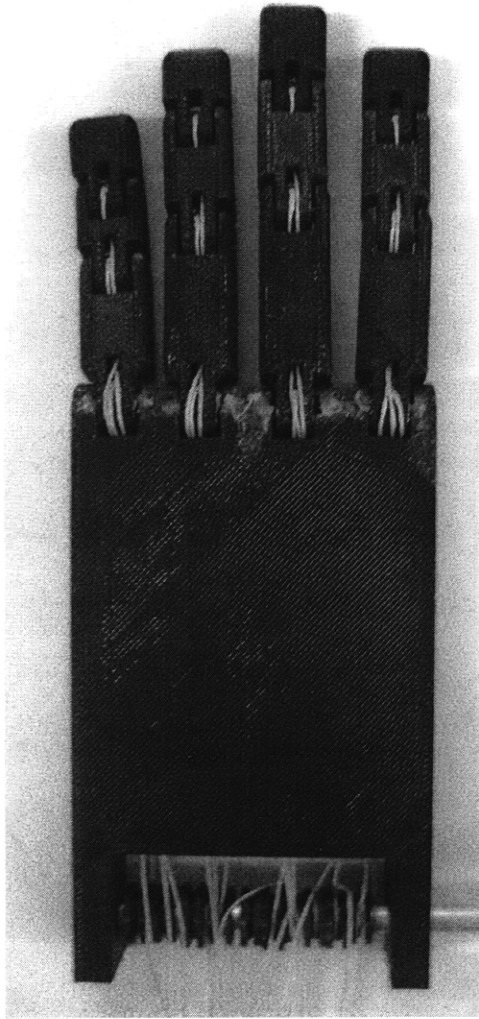


Figure 7: 3d printed hand. Kevlar cables are attached to pulleys at one end of each finger segment and run down through the fingers and hand to attach to pulleys on the same shaft. When driven by a DC motor, the shaft turns and moves all fingers in a coordinated fashion.

References

- [1] Xiong, Caihua, Han Ding, and Youlon Xiong. Fundamentals of Robotic Grasping and Fixturing. Shanghai: World Scientific, 2007.
- [2] Mason, Matthew, and Kenneth Salisbury. Robot Hands and the Mechanics of Manipulation. Cambridge: The MIT Press, 1985.
- [3] Brown, Christopher and Harry Asada. “Inter-Finger Coordination and Postural Synergies in Robot Hands via Mechanical Implementation of Principal Components Analysis.” IROS 2007.
- [4] Rosmarin, Josiah, and Harry Asada. “Synergistic Design of a Humanoid Hand with Hybrid DC Motor – SMA Array Actuators Embedded in the Palm.” ICRA 2008.