Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Bio-Inspired Robotics Lab
Prof. Dr. Fumiya Iida

Internship Final Report

Design and Simulation of a Tendon-Driven Hot Melt Adhesive "Hand" Robot

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Supervised by:
Utku Culha

Author:
Melissa Lee

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Abstract

Unlike traditional hard robots, soft robots with their flexible bodies provide more degrees of freedom and more effective interaction with other soft bodies. However, soft robots are harder to simulate and control. This report presents a simple case-study of an educational project that introduces soft robotic research. In this project, a tendon-driven, hot melt adhesive, grasping robot with continuous joints was designed, constructed and simulated. The results show that construction of the robot is feasible; however, the simulation needs troubleshooting. A longer time frame would be needed to fully complete the simulation of the robot.

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Chapter 1

Introduction

Unlike traditional robots with rigid joints and bodies constructed from hard materials such as metal, soft robots have flexible bodies. Soft robots provide advantages such as intrinsic compliance, adaptability, deformability, and versatility. They also provide more effective interfaces for interactions with other soft or delicate bodies, i.e. humans [8]. Current soft robotics research at the Bio-Inspired Robotics Laboratory mainly focuses on the properties and applications of hot melt adhesive (HMA). Due to its elasticity, malleability and adhesiveness, HMA is a cost-efficient soft robot material. Since HMA can easily be transformed from solid to liquid, it can be molded into an infinite variety of configurations. However, HMA and other soft materials are difficult to model and simulate.

This project is a case-study of an educational project intended to introduce and provide exposure to soft robotics through the design, construction and simulation of a soft robot. The goal of this project was to explore the feasibility of such an educational project which utilizes HMA for the construction and SimMechanics for the simulation of a soft grasping robot, with a given time frame of two months. Additionally, this project explores the simulation of continuous joints.

1.1 Human Hand Anatomy

The simple robot of this project was inspired by the grasping behavior of the human hand. In the anatomy of the human hand, each finger, excluding the thumb, is comprised of the following bones, which extend distally from the wrist: metacarpal, proximal phalanx, middle phalanx and distal phalanx (Fig. 1.1). The metacarpals of the fingers and the thumb are connected by flesh to form the palm of the hand. The joint between the metacarpals and the proximal phalanx is the metacarpophalangeal joint. The proximal interphalangeal joint and the distal interphalangeal joint are the joints between the phalanges of the fingers as shown in Figure 1.1 [2].

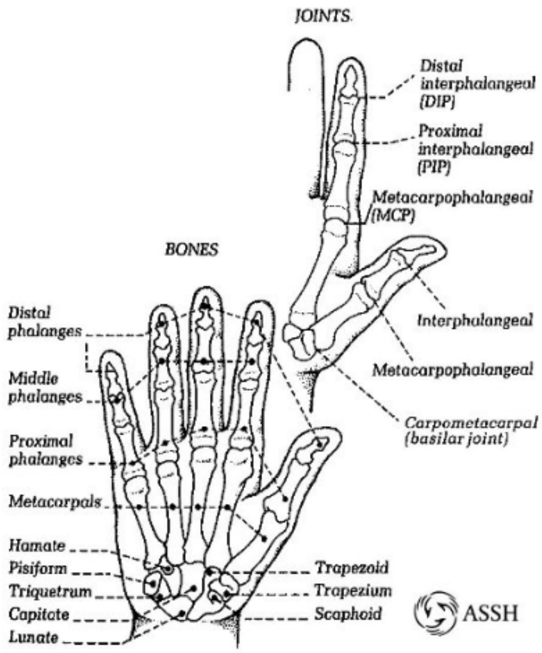

Figure 1.1: Diagram of hand anatomy [1].

According to the American Society for Surgery of the Hand, prehensile movement of the hand is for "grasping, carrying and releasing an object." The thumb is generally used for more precise actions. When the thumb is not used to grasp an object, those grips are generally "power grips." There are four main grip patterns of the hand: hook grip, cylindrical grip, spherical grip, and fist grip. Since the fist grip is usually for grasping narrow objects, it is the only grip that flexes the distal interphalangeal joint, proximal interphalangeal joint as well as the metacarpophalangeal joint [2]. Since this allows for more variability in the size of the object to be grasped, the grasping behavior of the robot was modeled after the fist grip. According to the Tubiana, the grip is limited by the maximum flexion angles for each joint, which are 85° , 115° and 80° for the metacarpophalangeal, proximal interphalangeal and distal interphalangeal joints, respectively [10]. Although the fist grip uses the thumb for opposition, the robot does not include a thumb for simplification. Also, although the "asymmetry of the hand greatly increases functional properties," due to time constraints and simulation simplification, the robot was simplified to a symmetric hand [9].

The flexion and extension of the human hand relies on a tendon-driven system of flexor tendons, extensor tendons and extrinsic muscles that actuate the tendons [7]. Tendon sheaths, double-walled membrane, surround the flexor and extensor tendons to "prevent 'bowstringing' and maximize efficiency of joint movement" [2]. In order to keep the robot simple, only a flexor tendon was incorporated in the design. The extension of the fingers of the robot relied on the elasticity of the HMA.

1.2 Continuous Joints

Many previous tendon-driven robots inspired by the human hand consist of discrete joints. Although discrete joints allow for better precision and are easier to control, their mechanical constraints limit the movement of the robot and its adaptability to its environment. Continuous joints, a possibility in soft robots, provide advantages not available in discrete joints. Having fewer mechanical constraints, continuous joints provide more degrees of freedom. They are also more dexterous, allowing for better adaptability. The intrinsic compliance of continuous joints allow for more effective interaction with other soft bodies [6]. Past studies have investigated the ability of tendon-driven, continuous, soft prosthetic hands, with compliant active and passive joints, in enhancing grip functionality while keeping the control simple. Although a continuous body with compliant joints that rely mainly on deformation of the material allow for “simplified manufacturing,” “reduced maintenance” and “better performance,” it is more difficult to model and control than a robot with discrete joints [5]. This project explores the possibility of using simulations to better understand continuous joints.

Chapter 2 will describe the details of the design and simulation of the robot. Subsequently, Chapter 3 will present and discuss the results of the robot construction and simulation. Lastly, in Chapter 4, final conclusions and plans for future studies will be presented.

Chapter 2

Methods

In this chapter, the physical design of the robot and the SimMechanics simulation of the continuous joints and tendon-pulley system of the robot will be described.

2.1 Physical Design

The design of the robot is a tendon-driven grasping system inspired by the human hand. The grasping motions of the robot emulate the power grip of the hand. However, in the design of the robot, the thumb was disregarded, and the palm was used for opposition for the grip. The following describes the final design of the robot, chosen after a few initial prototypes. The robot consists of four fingers that are rigidly connected to a palm at 90 degrees. The palm was constructed by gluing seven sticks of HMA together. Each finger, a single stick of hot melt adhesive (HMA), modeled after the human finger, consists of a distal phalanx, a middle phalanx, a proximal phalanx and two underactuated joints (as seen in Fig. 1.1). The lengths of the phalanges of the robot were taken from the average of the phalanx proportions in all fingers in relation to their respective distal phalanx, given in “Proportions of Hand Segments.” The proportions were then scaled so that the distal phalanx was two centimeters long. The lengths of the robot phalanges are shown in Table 2.1.

Phalanx	**Length [cm]**
Distal	2
Middle	2.75
Proximal	4.8
Metacarpal	7.4

Table 2.1: Lengths of robot phalanges.

Each joint was constructed by melting a one centimeter section of the HMA finger, reducing the stiffness to allow for bending. The flexing motion of the robot fingers follow the motion of the hand, in which the flexion of the joints begin at the proximal joints and proceed distally as shown in Figure 2.1 [3].

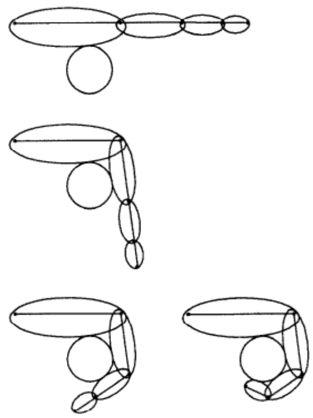

Figure 2.1: Diagram of planar power grip flexing motion [3].

Each finger has a fishing wire tendon along the underside to flex the finger. The tendons were glued to the distal phalanges with HMA, running through plastic tendon sheaths glued to each phalanx that prevent bowstringing. Unlike the human hand where the tendons continue along the metacarpals, in the robot, the tendons continue parallel to the proximal phalanx, running through the metacarpophalangeal joint. This allows the motor to work less when flexing the fingers. All four tendons were attached to a 3-D printed shaft actuated by a 180-degree 1501MG servo motor with metal gears. The motor is visually controlled by the user via an Arduino board. The Arduino code allows the user to close, open, and return the hand to the initial open position. The motor pauses every five degrees in case the user would like to stop the robot. Figure 2.3 shows pictures of the robot at various angles.

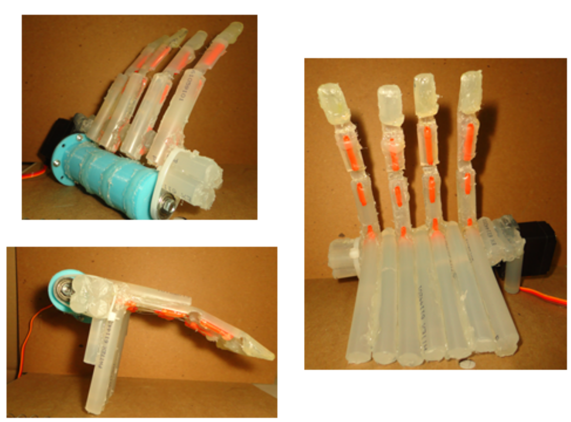

Figure 2.2: Pictures of the robot at various angles.

2.2 SimMechanics Simulation

The robot was simulated using Second Generation SimMechanics blocks. In the simulation of the robot, there are two main concepts: the simulation of the continuous joints and the simulation of the tendon system.

Since it is not possible to directly simulate a continuous body, a lumped parameter model of the continuous joints was simulated in SimMechanics. Each continuous joint in the simulation consisted of multiple rigid blocks, equal in dimensions and density, connected by revolute joints with equal stiffness and damping. The density used for the blocks was 970 [kg/m^3] [11]. The stiffness and damping was added to each joint by applying the internal mechanics of the revolute joint. The stiffness of the proximal interphalangeal joint was 2.004 x 10^{-4} [N-m/deg] and of the distal interphalangeal joint was 4.267 x 10^{-4} [N-m/deg], approximately. These values were found experimentally by measuring the torque required to displace the joint to various angles. The torque and angle data were plotted, and the spring constant (slope of the best-fit line) was calculated using the curve fitting tool in MATLAB. The maximum flexion angle of the proximal interphalangeal joint is 80 ° and of the distal interphalangeal joint is 115 ° . Using Simulink, the physical constraints of the joints were simulated by applying a position control to each joint. Testing of the simulation utilized a perpendicular force applied to the distal phalanx.

For the tendon simulation, extension of the tendons were assumed to be negligible. Since it is not possible to physically simulate tendons in SimMechanics, the alternative is to calculate the geometric relationships of a virtual tendon-pulley system attached to the phalanges of the robot. For the simulation, each joint had a pulley of arbitrary radius attached to the relatively non-moving phalanx. For instance, regarding the distal interphalangeal joint, the distal phalanx moves in relation to the middle phalanx. Therefore, the pulley is attached to the middle phalanx. For the robot simulation, a virtual tendon is attached to the distal phalanx and runs to the pulley of the distal interphalangeal joint. Wrapping around the first pulley, the virtual tendon goes to the pulley of the proximal interphalangeal joint. Wrapping around the second pulley, the tendon runs parallel to the proximal phalanx. Figure 2.3 shows a rough graphical representation of the tendon-pulley system.

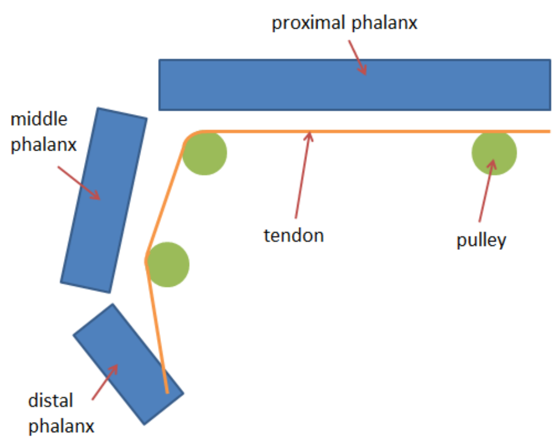

Figure 2.3: Diagram of tendon-pulley system for simulation.

The vectors along the tendon at each attachment point to either a phalanx or a pulley were calculated and scaled by the force applied by the motor torque. An advantage of using SimMechanics is that it automatically tracks the position of each solid body with relation to the frame of the world. Using this, the simulation is able to track the displacements as force from the motor is applied.

Chapter 3

Results

In this chapter, the results of the robot construction and SimMechanics simulations will be presented and discussed.

The construction of the robot was achieved. The grasping of the robot was tested with a wood cube. Although only two or three fingers made contact with the block, the elasticity of the joints and fishing wire tendon allowed the fingers to grip the block while the non-touching fingers continued to close until the user stopped the motor. This grasping behavior emulates that of a human hand. It was observed that the continuous joints of the robot acted like discrete joints until it came in contact with the object. However, the behavior of the continuous joints after contact with the object was hard to observe. Therefore, a simulation of the robot is advantageous to visualize and analyze the behavior of the continuous joints.

The simulation of the lumped parameter model of the continuous joints of the robot contained two discrete parts with three joints, as shown in Figure 3.1. The desired minimum discrete parts of the continuous joint simulation was ten parts as shown in Figure 3.2. However, compiling a simulation of more than two discrete parts caused the program to crash. The source of the error is unknown; however, it is suspected that the error stems from the limit on the calculation capacity of the computer, since the amount of time the simulation runs varies from computer to computer. Originally, the stiffness for the joints were chosen such that the proximal interphalangeal joint and distal interphalangeal joint had effective stiffness of 2.004×10^{-4} [N-m/deg] and 4.267×10^{-4} [N-m/deg], respectively. The stiffness of the discrete joints in the continuous joints were treated as torsion springs in series. The damping values that gave the least underdamped behavior without causing the program to crash were chosen by trial and error. The position control that dictates the physical constraints for maximum joint angles were effective for one continuous joint. However, once control for the second continuous joint was added, the constraints were only achieved after many oscillations. It may be more effective to utilize a P-D control to apply physical constraints.

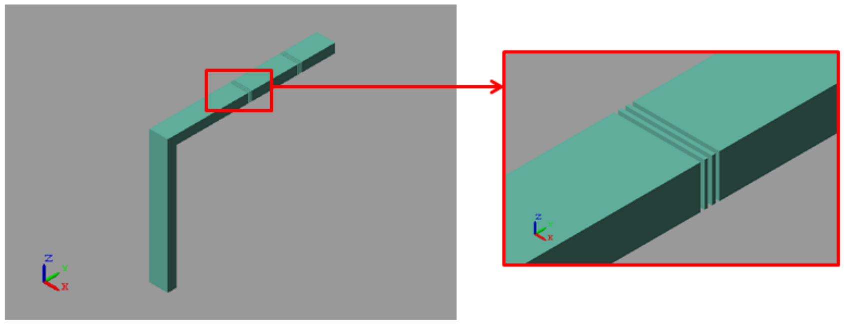

Figure 3.1: Screenshot of SimMechanics simulation of finger with continuous joints with two discrete bodies.

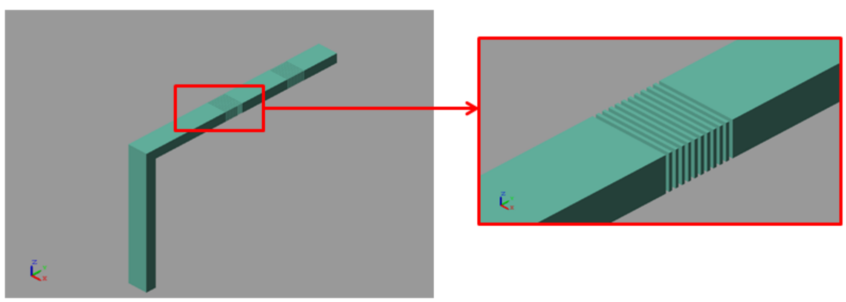

Figure 3.2: Screenshot of SimMechanics simulation of finger with continuous joints with ten discrete bodies.

The geometry relations for the tendon-pulley system were calculated but not implemented, since the continuous joint model is unfinished and needs troubleshooting. The tendon-pulley system was set up using Simulink and Second Generation SimMechanics blocks for a robot finger with two discrete joints. If the tendon-pulley were implemented in the continuous joint system, then each discrete rigid body in the continuous joints would have a pulley associated with it.

Chapter 4

Conclusions and Future Work

As a case-study for an educational project on soft robotics, a tendon-driven, soft, grasping robot inspired by the human hand was designed and simulated. In this chapter, the results of the design and simulation will be summarized and areas for future work for each respective part will be discussed.

4.1 Physical Model

The robot was constructed out of hot melt adhesive (HMA), utilizing fishing-wire for tendons and a servo motor for the actuating muscle. The grasping behavior of the robot resembles that of the human hand. However, over time, the robot fingers deformed, returning to a gradually more flexed position when the motor was brought back to its initial position. To counter this problem, it would be beneficial to add an extensor tendon to the back of the fingers. Additional future improvements to the physical model include incorporating friction in the tendon sheaths to reduce reliance on the motor in keeping the robot in a certain grasp position and incorporating sensors for grasping control. In the construction of the robot joints, it was difficult to maintain a consistent thickness throughout each joint manually. It would be beneficial to explore the possibility of 3-D printing the HMA robot to ensure homogeneity in joint thickness within the joint and joint dimensions among corresponding joints among the fingers.

4.2 Simulation

Simulation of the grasping robot was broken into two main concepts: simulation of the continuous joints and simulation of the tendon-pulley system. A lumped parameter model of the continuous joints of the robot was simulated by dividing each joint into two discrete bodies. The current simulation does not have working physical constraints on the joints and depends on control gains to apply physical constraints. However, since control gains were not as effective as expected, another method would need to be developed to apply the physical constraints. For future study, improvements to the simulation would need to be made in order to minimize memory usage for calculations, allowing for better resolution of the lumped parameter model of the joints. Although the geometric relations for the tendon-pulley system simulation were calculated, the tendon-pulley system was not implemented. For future study, the tendon-pulley system simulation would need to be combined with the continuous joint simulation for a complete simulation of a robot finger. The simulation would then need to be duplicated three times with the correct frame relations in order to simulate the whole robot. It would be beneficial to develop a method to validate the simulation. A validated simulation would be advantageous in analyzing continuous joints and could lead to predicting the behavior of the joints when the robot comes in contact with its environment.

As an educational project, this project was effective in introducing and creating exposure to soft robotics. However, a longer time frame than two months would be necessary for a fully developed project. Possible future case-studies for education projects could explore a tendon-driven continuous arm for grasping or a robot that utilizes continuous joints to maneuver in tight places.

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