Humanoid Hand

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Things to change based on feedback

- Color of text vs background color (slide 33) done
- Final physical model with component labels
- Condense literature review into key points, less wordy 1/6
- Add gifs and/or pictures to illustrate project progress and results
- Keep it as non-technical as possible; easy to understand
- Acknowledgement slide done
- Minor nitpicks, clean up professionalism (intersecting text, update QFD)

Project Description

A robotic hand that matches the capabilities of the human hand

$1500 given
$500 fundraised

<u>Sponsored by</u>:
Dr. Zach Lerner
Dr. Reza Razavian

Major Deliverables

- Spring semester
  - Mathematical modeling
  - Literature review
  - Simple prototyping
- Hardware status updates - gave us deadlines for building our final product.
  - Making small changes throughout the fall semester to meet these requirements
  - Due:
    - 33% - 9/22/25
    - 67% - 10/13/25
    - 100% - 11/3/25
- Team deadlines were made for the different steps for our product
  - Physical prototype - 3D Prints and assembly - 10/13/25
  - Code - 11/1/25
  - Electronics - 11/1/25

Success Metrics

To be successful:

- Able to play a piano
  - Needs to exert a downward force of 1 Newton
  - Needs to be agile and move at a 1/16th note speed at 120 BPM
- Able to catch a ball
  - Has the speed to close the hand
  - Needs to have the strength to hold the ball without movement for 30 seconds
- Needs to meet all customer and engineering requirements
- 80% of tests need to be passed
- Needs to look sleek: wires and electronics as "uncluttered" as possible

Customer Requirements

1. Strong enough to play the piano and catch a ball (CR1)
2. Fast enough to play the piano and catch a ball (CR2)
3. Accurate dimensions (CR3)
4. Accurate weight (CR4)
5. Within budget (CR5)
6. Many degrees of freedom (CR6)
7. Uses standard form of power to function (CR7)
8. Does not overheat (CR8)
9. Has basic and functional UI (CR9)
10. Reliable (CR10)
11. Precision of motion (CR11)

Engineering Requirements

1. Grip force of 45-50N (ER1)
2. Time from full extension to full closure 200-250ms (ER2)
3. Within 1-1.5 scale of average person’s hand and forearm (ER3)
4. Approximately 3-4kg (ER4)
5. Cost of manufacturing <$1500 (ER5)
6. 15 degrees of freedom (ER6)
7. Operates with 1-3 120V plugs (ER7)
8. At high operating load, no component exceeds 75°C (ER8)
9. Score 4/5 on a qualitative survey (ER9)
10. Each joint operable near 10k motions (ER10)
11. Able to predict finger placement within +/- 5mm based on sensor data (ER11)

House of Quality

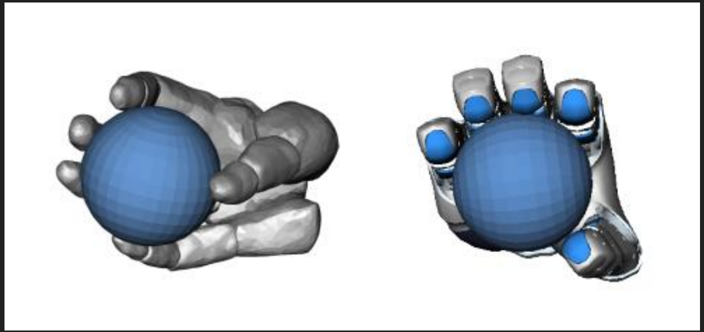
		Technical Requirements										
Customer Needs	Customer Weights(1-5)	Grip Force between 45-50N	Time from full extension to full closure is 200-250ms	Approximate size of human hand(1-1.5 scale)	Apx 3-4kg	Cost of manufacturing<$1500	apx 15 DOF	Operates with 1-3 standard 120V plugs	At room temperature under extreme load, no component exceeds 75C	Lerner and Reza give the operation an average of 4/5 scoring	Each joint ensured up to 10k motions	Able to predict finger segment placement within +/- 5mm based on sensor data
Strength	3	9	3	3	3	9	9	3	3	3	9	3
Speed	5	3	9	3	1	9	9	3	3	3	1	3
Accurate dimensions	2	3	3	9	9	3	9	0	0	3	0	3
Accurate weight	1	9	9	9	9	3	3	0	0	3	0	3
Budget	4	9	3	3	9	9	3	0	0	9	0	0
Many degrees of freedom	4	3	3	3	3	9	9	0	0	9	3	3
Uses stand form of power to function	5	1	1	9	9	9	1	9	3	9	0	0
Does not overheat	5	0	0	0	0	0	1	1	9	3	9	0
Has basic and functional ui	4	1	1	1	3	3	3	0	0	9	0	1
Reliable	4	3	1	0	0	0	1	0	9	3	9	0
Precision of motion	4	3	3	9	3	9	3	0	0	9	0	9
Technical Requirement Units		N	s	s	kg	$	deg	#	°C	min	#	mm
Technical Requirement Targets		160	0.3	250	4	150	20	3	75	10	10k	5
Absolute Technical Importance		126	114	160	158	246	170	45	141	222	44	85
Relative Technical Importance		7	8	4	5	1	3	10	6	2	11	9

Benchmarking

1. Shadow Hand by Shadow Robot
   a. Has 24 DOF, >100 sensors, tactile sensing
2. Dex Hand
   a. Great open source for referencing and helping solve our problems
3. Tesla's Optimus robot
   a. 22 DOF using 6 motors
   b. Demonstrates high degrees of freedom under actuation
   c. Tactile sensing

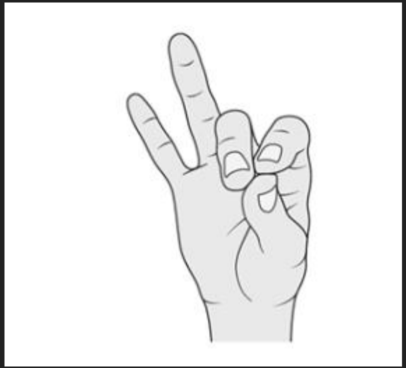
Literature Review – Kinematic Modeling and Anatomy

- Kinematic Modeling of the Human Hand for Robotics
  - What types of movements are necessary to make a humanoid hand
  - What movements make up different shapes of the hand



3D Model of Hand gripping a ball with MRI

- Functional Anatomy and Biomechanical Concepts in the Hand
  - How different components move under weight or free



Tripod/Pincer grip

Literature Review - Noah (C++ and Dexterity)

The C++ Programming Language [49] - This book, written by the creator of the C++ programming language, covers the core concepts of C++. It will serve as an excellent guide in learning C++ for the programming of the hand.

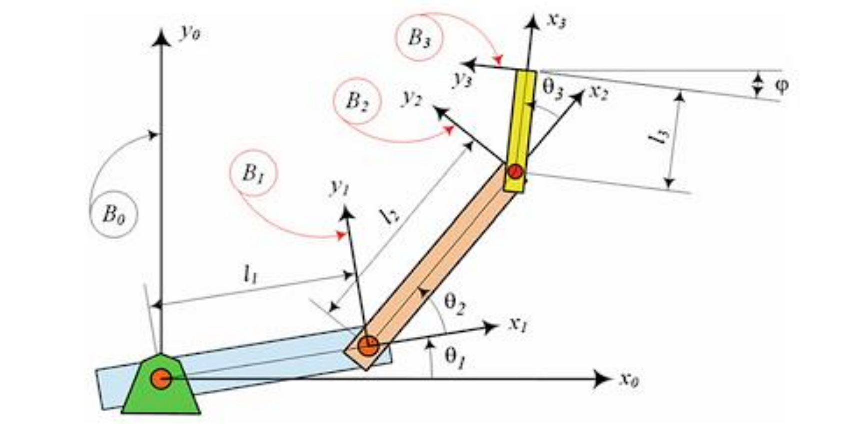
Practical Robotics in C++ [50] - This book is tailored to programming robotics in C++. The book gives practical examples and detailed walkthroughs for the reader. This book will also serve to inform the programming of the hand.

A Review of Robot Learning for Manipulation [51] - This journal article covers the current state of machine learning as it applies to robots tasked with manipulating objects in their environment. This article will serve as a resource to refer to in considering the integration of machine learning into the hand.

On Dexterity and Dexterous Manipulation [52] - This journal article outlines some of the essential postures and mechanics of robotic hands as it relates to grasping objects. This informs the joint design and actuation style of the hand. These subsystems are critical to the hand’s performance.

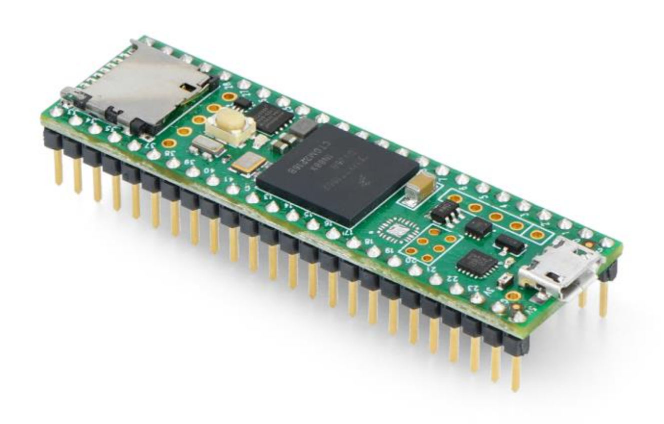
Literature Review - Arduino & Kinematics

- Theory of Applied Robotics: Kinematics, Dynamics, and Control (3rd Edition)
  - Forward and Inverse kinematics



Inverse Kinematics Diagram of a 3-Link Planar Manipulator

- Arduino Robotics
  - Write code to communicate with motors
  - Great C++ compatibility



Arduino Teensy 4.1: Microcontroller for Hand's Motors

Literature Review - Markus (Examples and Kinematics)

A low-cost and modular, 20-DOF anthropomorphic robotic hand: Design, actuation and modeling [20] - This paper provides an in-depth analysis of actuation techniques and explores the trade-offs between cost, complexity, and dexterity in robotic hand development.

Excursion of the flexor digitorum profundus tendon: A kinematic study of the human and canine digits [21] - This article investigates the movement of flexor tendons in both human and canine digits, providing essential data for modeling tendon excursions in robotic hands. These motion patterns are critical for designing a tendon-driven actuation system that achieves realistic movement.

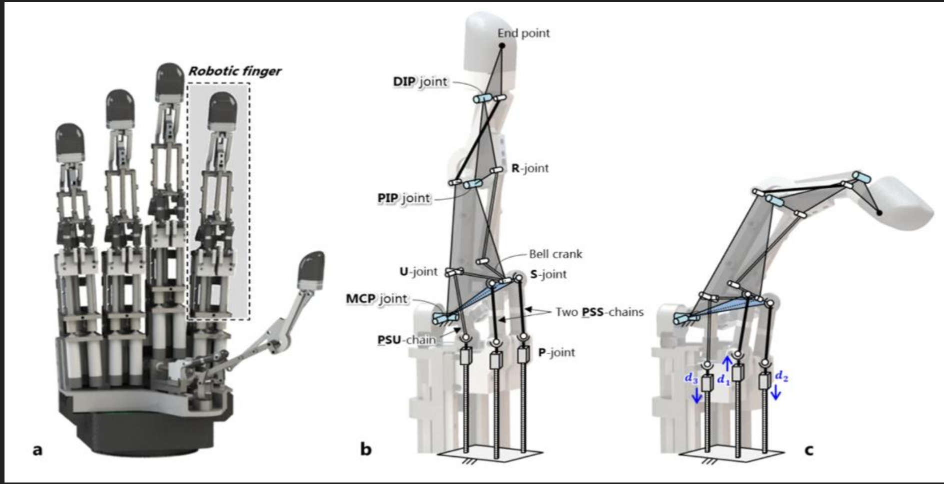
Bionicsofthand[22] - This webpage describes an advanced soft robotic hand that incorporates biomimetic principles and pneumatic actuation. The information provided influenced material selection and actuation methods for our project.

Literature Review - Servos and Robotic Hands

- Servos Explained
    - How do servos work?
    - What components are inside a servo?
    - What can a servo work for?

- **Integrated linkage-driven dexterous anthropomorphic robotic hand robotic hand**
    - Linkage mechanism
    - 15 Degrees of freedom

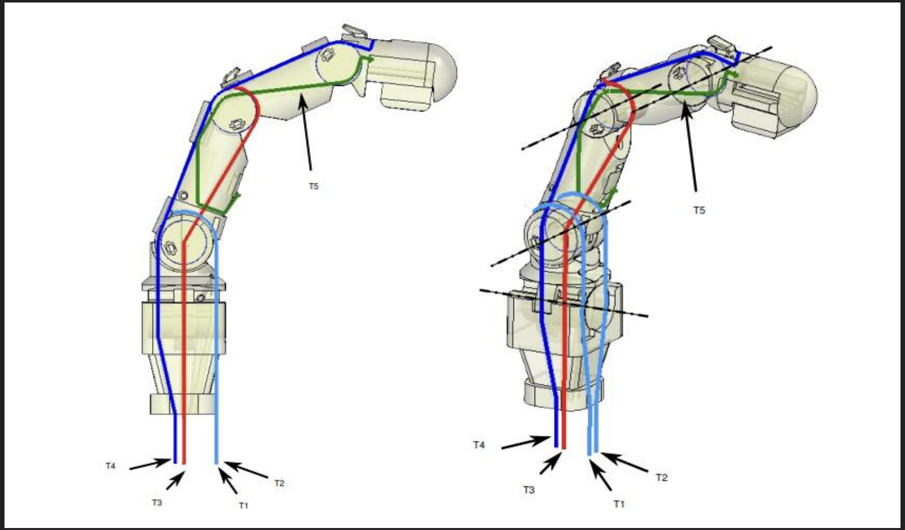
Hitec HS-422 deluxe Servo



Design of linkage driven robotic hand

Literature Review - David (Control and Examples)

- Design and control of robotic hands
  - Tendon driven
  - Control code
  - Mechanical linkage
- The Put Hand/ Touch Hand
  - Similar Project
  - Gained inspiration
  - Various Actuation methods



Tendon schematic inspiration

The PUT Hand

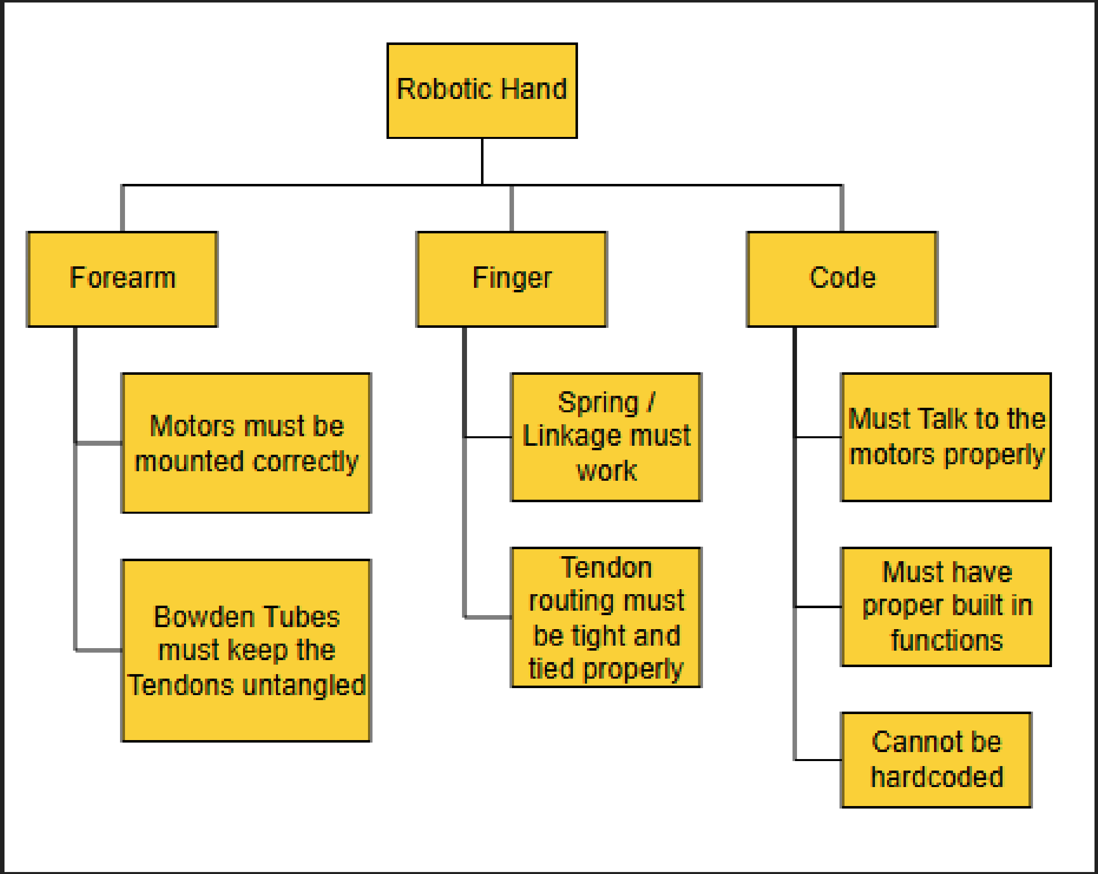
Mathematical Modeling

Calculation	Equation(s)	Application	Requirement Met	Validation
Projectile motion	$x_f=x_0+v_{0x}t$ $x_f=(v^2\sin 2\theta)/g$	Catching a ball	Dexterity and reaction speed	Dynamics Assumptions
Finger tip joint inference	$\theta_{Tip}=.667\theta_{Mid}$ $\theta_{Tip}=.556\theta_{Mid}$ $\theta_{Tip}=.333\theta_{Mid}$	Coding, ease of design, mechanical linkages	Biomimetic and natural motion	Speculation Grip Angles
Motor Speed	$\omega = \frac{d}{rt}$	For Motor Selection	Hand actuation speed	Speculation Reaction time
Shear Stress	$V = \frac{T}{r} + F$ $\tau = \frac{F}{A}$	For material selection for joints	Number of actuations	Speculation Average Material
Fingertip location (x,y,z)	$x_3 = x_2 + L_3\cos(\theta_1+\theta_2+\theta_3)\cos(\phi)$ $y_3 = y_2 + L_3\sin(\theta_1+\theta_2+\theta_3)\cos(\phi)$ $z_3 = z_2 + L_3\sin(\phi)$	Finding location of fingertip in terms of the base joint	Control of the fingers	Implementing code Real finger lengths

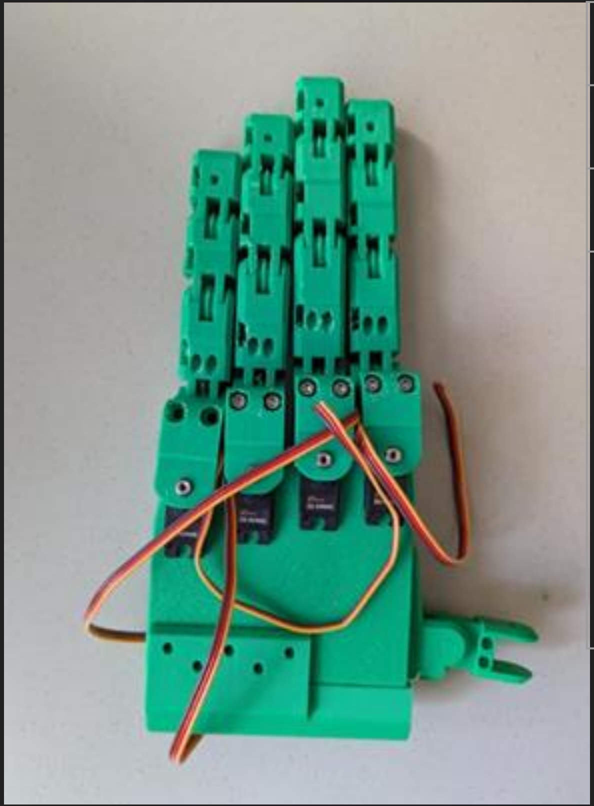
Mathematical Modeling

Calculation	Equation(s)	Application	Requirement Met	Validation
Hand Measurements	N/A	Have exact measurements of joints and segments	Average hand size and upper limit	Speculation Average Measurements
Power	P = V*I	Power consumption	Reasonable power consumption	Equations used agree with what was learned in PHY-262, EE-188 Compare results to power consumption of real-world electrical devices
Motor Torque	F = ma T = Fr	Inform motor selection	Establish minimum required motor torque	Equations and their application agree with the basic principles of static analysis Required motor torque agrees with reason
End-Effector Velocity	Various matrix solutions	Determining the velocity vector of a fingertip	Speed and dexterity	Previous kinematic equations and literature

Functional Decomposition



Concept Generation



Pros	Pros
• Simple design	• Includes servo connections • Spring for extension • Motor slots for easier tensioning
Cons	Cons
• No cut outs for servo connections • No way to extend finger tip • No wrist, forearm	• No wrist • Tendon routing is off

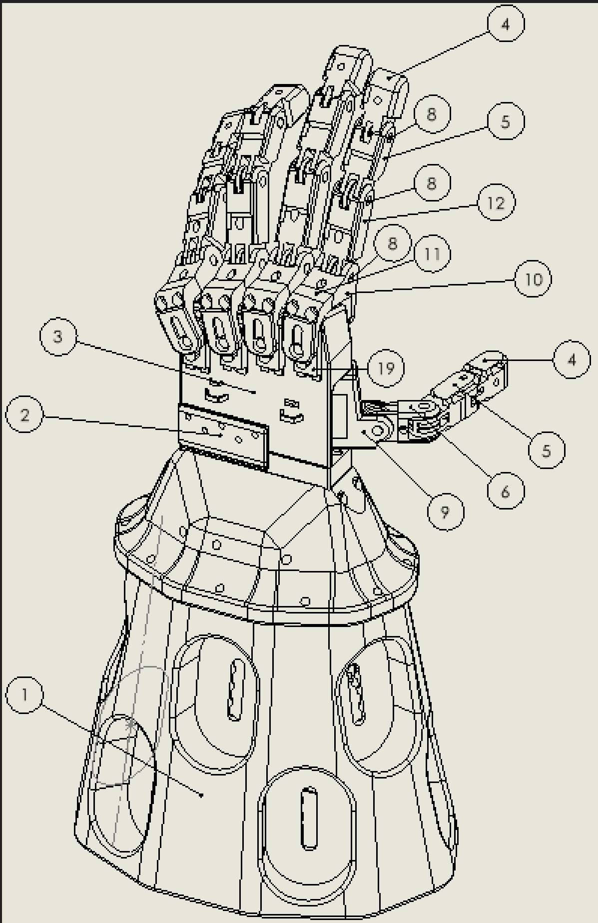
Selection Criteria

- **Grip force**: Calculated by tendon analysis and joint torque analysis as well as shear stress on fingers. We Know a maximum allowable force based on our estimated parts.
- **Grip Speed**: Calculated through motor analysis done in previous slides.
- **Hand Size**: 1.5 times average hand size was the goal.
- **Manufacturing Cost**: We set out to stay below our budget of $2000 ($1500 granted, $500 fundraised). We accomplished this goal and ended with $475 remaining.
- **DOF**: We set out to have 15 DoF and met this goal with our final design.
- **Power**: Power is supplied via a single power bank and operates at a max of 35V.

Concept Selection - Specification Table

Specification	Importance	Units	Target	Tol.	Comments
Grip Force	7	N	45-50	5	Average grip force of adult
Grip Speed	8	ms	250-300	50	Average reaction time of an adult
Size of Average hand	4	mm	190x85	50x25	Easy to store and more intuitive
Weight of average hand	5	kg	3-4	1	Portable and reflect biology
Cost of Manufacturing	1	$	1500	250	Budget
Many DOF	3	#	15	1	Reflects Biology
Easy to power	10	V	120	0	Operates off US electrical outlet
Easy to use interface	2	N/a	4/5	.5	Score on qualitative survey
Does not Overheat	6	°C	75	5	Components do not exceed temp.
Precise and Accurate Motion	9	mm	5	1	Position is known within this area
Longevity	11	#	10,000	250	Able to be actuated near infinite life

Concept Selection - Current CAD



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	Forearm_New2 (2)		1
2	palm_bottom(1)		1
3	palmLowerLoops		1
4	fingerTipPretensionedSpringPoint75		5
5	fingMidsectionSpring		2
6	fingsplay (1)		1
7	7804K106	Stainless Steel Ball Bearing	20
8	pin_2		15
9	thumbbase2 (1)		1
10	finger_interface_bottom		4
11	finger_interface_top (1)		4
12	fingerBase		1
13	fingerBase_middle		1
14	fingMidsectionSpring_middle		1
15	fingerBase_ring		1
16	fingMidsectionSpring_ring		1
17	fingerBase_pinky		1
18	fingMidsectionSpring_pinky		1
19	servo		5

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL

Schedule - Overview

Spring Semester:
Phase 1 – Establishing Finger design / Joint Design
Phase 2 – Finger prototype
Phase 3 – Whole hand design (Initial)

Fall Semester:
Phase 4 – Startup of Semester
- Updating designs

Phase 5 – Building and Prototyping
Phase 6 – Efest, Wrap up, and Client Hand off

Schedule - Example

Phase 5 (Building)						
Hardware Status Update - 33%	Team	100%	8/28/25	9/22/25	60.00	50.00
Finger and Palm Print	Noah	100%				
Electrical Install	Noah, Tyler, Markus	100%				
Slides	Justin, David, Joseph	100%				
Hardware Status Update - 67%	Team	100%	8/28/25	10/13/25	60.00	50.00
Thumb Print	Noah	100%				
Electrical Install / code	Noah, Joseph, Justin	100%				
Slides	David, Tyler, Markus	100%				
Hardware Status Update - 100%	Team	100%	8/28/25	11/3/25	60.00	50.00
Forearm Print	Noah	100%				
Full electrical and control system	Noah, David, Markus	100%				
Slides	Justin, Joseph, Tyler	100%				

Budget

	Budget sheet for Robotic Hand Capstone					
	Budget Given by Client: $1500			Fundraised Funds: $500		
	Total Budget					$2,000
	Item	Description	Do we have it?	Price per Unit	Number of Units	Total price
1	Breadboard kit	4PCS breadboard kit	Yes	$7.00	1	$7.40
2	Electronics	22 Guage silicon wire	Yes	$20.00	1	$23.35
3	Servos	DS939MG Digital Metal Servo	Yes	$9.00	5	$80.36
4	Microcontroller	PJRC Teensy 4.1	Yes	$32.00	2	$93.84
5	Bearings	Bearings	Yes	$10.00	1	$41.44
6	Motors	GM3506 Brushless Gimbal Motor	Yes	$58.53	10	$644.45
7	Potentiameter	Angle sensors	Yes	$1.34	25	$30.20
8	Filament	Onyx Filament	Yes	$209	1	$259.42
10	Actuation	Torsinal spring	Yes	$7.00	1	$18.38
11	Computation	Driver board	Yes	$78.90	1	$83.84
12	Actuation	Bowden tubes	Yes	$3.00	1	$17.92
13	Load cell	Testing	Yes	$9.88	1	$9.88
14	S hook Scale	Testing	Yes	$29.66	1	$29.66
15	Thermometer	Testing	Yes	$16.99	1	$16.99
16	power draw	Testing	Yes	$29.99	1	$29.99
17	power supply	Actuation	Yes	$58.78	1	$58.78
18	Adapters	Actuation	Yes	$33.13	1	$33.13
19	PLA	Filament	Yes	$28.36	1	$28.36
20	Springs	Actuation	Yes	$17.46	1	$17.46
	Estimated Remaining Budget					$475.15
	Actual Remaining Budget					$475.15

Bill of Materials

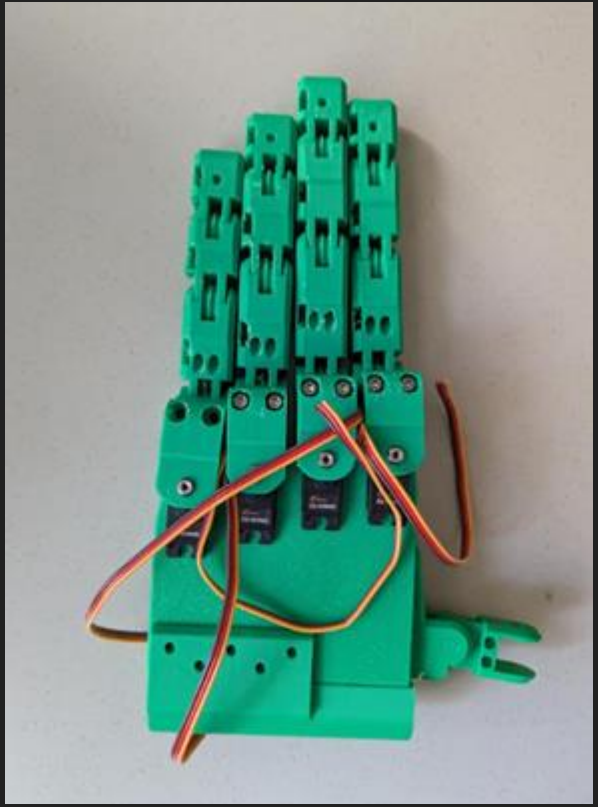
Part	Quantity	Price	Total Price	Make/Buy	Manufacturer	Lead Time	Part Status
Motor							
iPower GM2804 Gimbal Motor w/ AS5048A Encoder	10	42.97	429.70	Buy	Robot Shop	2 weeks	in house
Servo Motor	6	8.99	53.94	Buy	Amazon	1 week	in house
3D Printed Parts							
PLA Prototyping Filament	1	14.99	14.99	Buy	Amazon	1 week	in house
Onyx Filament	1	209.00	209.00	Buy	MatterHackers	2 weeks	in house
50cc Carbon Fiber Spool	1	150.00	150.00	Buy	Markforged	2 weeks	in house
3D Printed Fingers	4	0.00	0.00	Make	Us	10 hours	manufactured
3D Printed Thumb	1	0.00	0.00	Make	Us	10 hours	manufactured
3D Printed palm	1	0.00	0.00	Make	Us	10 hours	manufactured
3D printed forearm	1	0.00	0.00	Make	Us	10 hours	manufactured
Hardware - Computation							
Raspberry Pi	1	0.00	0.00	Buy	Raspberry Pi	2 weeks	in house
Teensy 4.1	2	31.50	63.00	Buy	Amazon	1 week	in house
Breadboard	1	6.49	6.49	Buy	Amazon	1 week	in house
Wire	1	19.13	19.13	Buy	Harfington	2 weeks	in house
Hardware - Actuation							
Dyneema Cord	1	32.99	32.99	Buy	Rocket-Fibers	2 weeks	in house
Bearings	25	1.05	26.25	Buy	Amazon	1 week	in house
Potentiometer	11	1.08	11.88	Buy	DigiKey	2 weeks	in house
Bowden Tube (1m/piece)	2	6.83	13.66	Buy	Amazon	1 week	in house
Hardware - Fasteners							
Lock Nuts (Pack of 25)	1	9.50	9.50	Buy	McMaster-Carr	2 weeks	in house
M3x30 Screw (Pack of 50)	1	7.85	7.85	Buy	McMaster-Carr	2 weeks	in house
M3x14 Screw (Pack of 50)	1	7.90	7.90	Buy	McMaster-Carr	2 weeks	in house
M3x8 Screw (Pack of 100)	1	8.00	8.00	Buy	McMaster-Carr	2 weeks	in house
M3x6 Screw (Pack of 50)	1	8.45	8.45	Buy	McMaster-Carr	2 weeks	in house
ESTIMATED PRICE	$		1,072.73				

Failure Modes and Effect Analysis (FMEA)

Product Name: Humanoid Hand		Development Team				Page No. 1 of			
System Name						FMEA Number 1			
Subsystem Name						Date 3/29/2025			
Component Name									
Part # and Functions	Potential Failure Mode	Potential Effect(s) of Failure	Severity (S)	Potential Causes and Mechanisms of Failure	Occurance (O)	Current Design Controls Test	Detection (D)	RPN	Recommended Action
1 Fingers/Frame	Force-induced deformation Impact deformation	Breaking of fingers and frame	6	Overstressing, high impact loads	6	Repeated application of forces and impacts	1	36	Select strong material
2 Bearings	High-cycle Fatigue Temp-induced deformation	High friction, inaccurate actuation	6	Inadequate venting, cyclic failure	5	Repeated actuation cycles (10k)	2	60	Choose appropriate commercial bearings or explore bushing joints
3 Pulleys	High-cycle Fatigue Force-induced deformation	Moderate to severe inability of actuation	6	High impact loads, cyclic failure	6	Impact analysis, repeated cycles	1	36	Select or machine strong pulleys
4 Tendon Cord	Ductile Rupture	Inability of operation	7	Inadequate routing, high stress loads	7	Tensile strength analysis, ductile failure test	3	147	Select a strong but flexible tendon cord
5 Tendon Housing	Abrasive wear	Lack of protection for tendon cords	2	Inadequate routing, cyclic failure	5	Friction factor analysis, repeated force application	5	50	Ensure flexibility in cable housing
6 Servos	High-cycle Fatigue	Limited DoF	6	Suboptimal power supply, cyclic failure, faulty wiring	6	Multimeter verification	7	252	Select high quality servos
7 Motors	High-cycle Fatigue	Moderate to severe inability of actuation	7	Suboptimal power supply, cyclic failure, faulty wiring	6	Multimeter verification	7	294	Select high quality motors
8 Angle Sensors	Force-induced deformation	Inability to interface	8	High impact loads, faulty wiring, noisy signal	7	Impact analysis, multimeter test	6	336	Select accurate and high quality angle sensors

Initial Prototyping 1

- Do Fingers and Palm interface correctly
- Adjustments need to be made to the servo placement and cutouts
- Change thumb servo, make cutouts for finger servos



Initial Prototyping 2

- How well does tendon and motor placement work
- Fewer bowden tubes, adjust tendon routing in forearm

Other Engineering Calculations

Calculation Constraints:

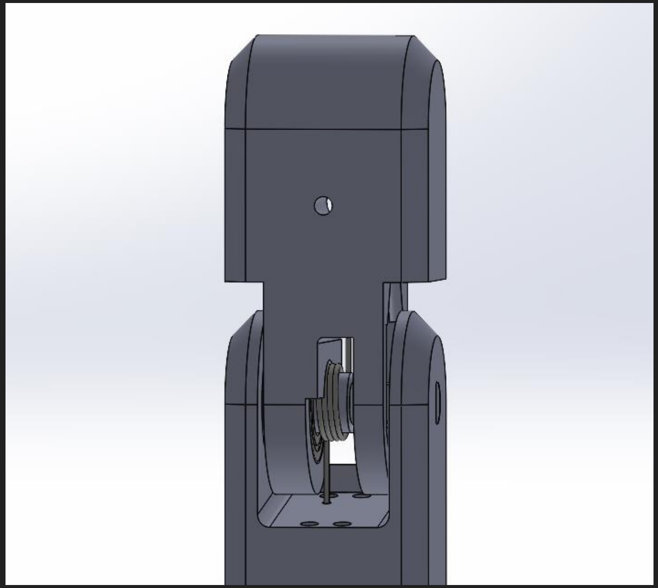
Wire Diameter × Number of Coils = Spring Length at Max Torque

T_{max} = Leg Length × Force

$T_{max} = 0.5 \text{ in} \times 0.225 \text{ lbf} \leq 0.1125 \text{ lbf-in}$

Spring Length at $T_{max} \leq 0.2$ in (5 mm)

Selected Part: 9271K667 (McMaster-Carr)



Finger Sub-Assembly Fitted with Selected Spring

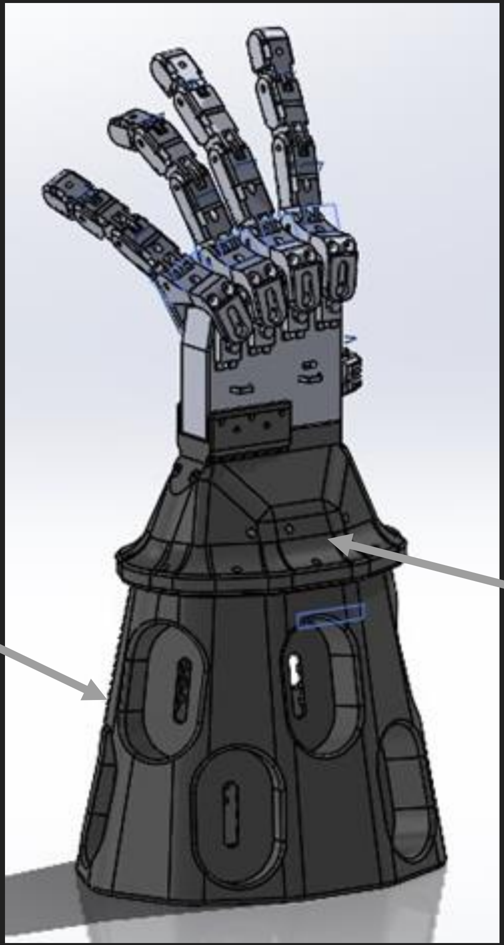
Meets length constraints:

$T_{max} = 0.13 \text{ lbf-in} > 0.1125 \text{ lbf-in}$

Spring Length at $T_{max} = 0.09 \text{ in} < 0.2$ in

Final Hardware

Adjustable Motor Placement

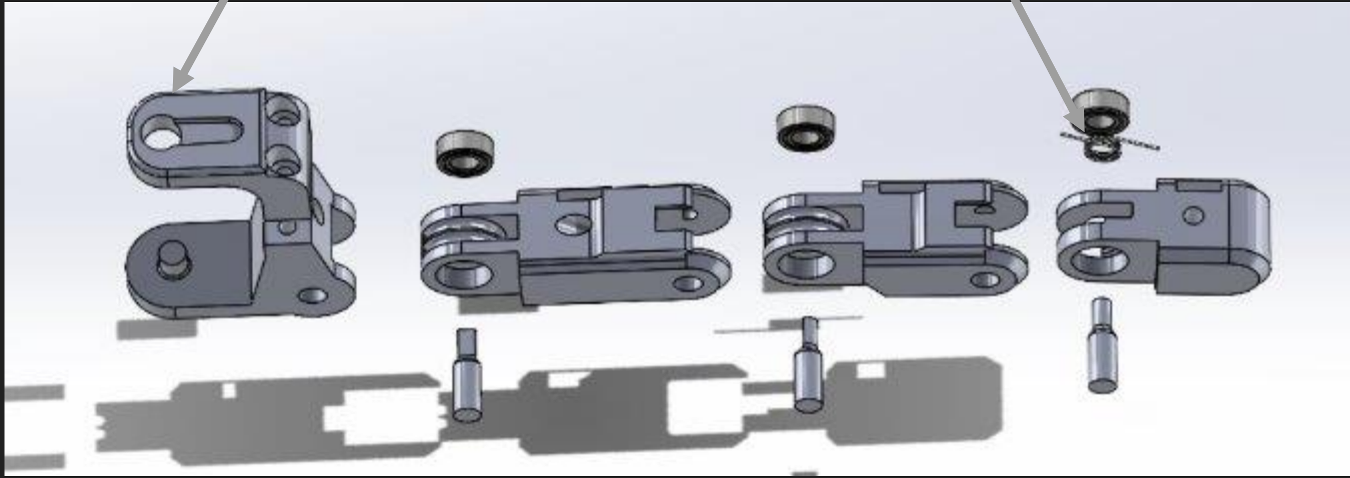


Bowden tube and tendon routing to back of hand

Final Hardware: Finger

Servo placement

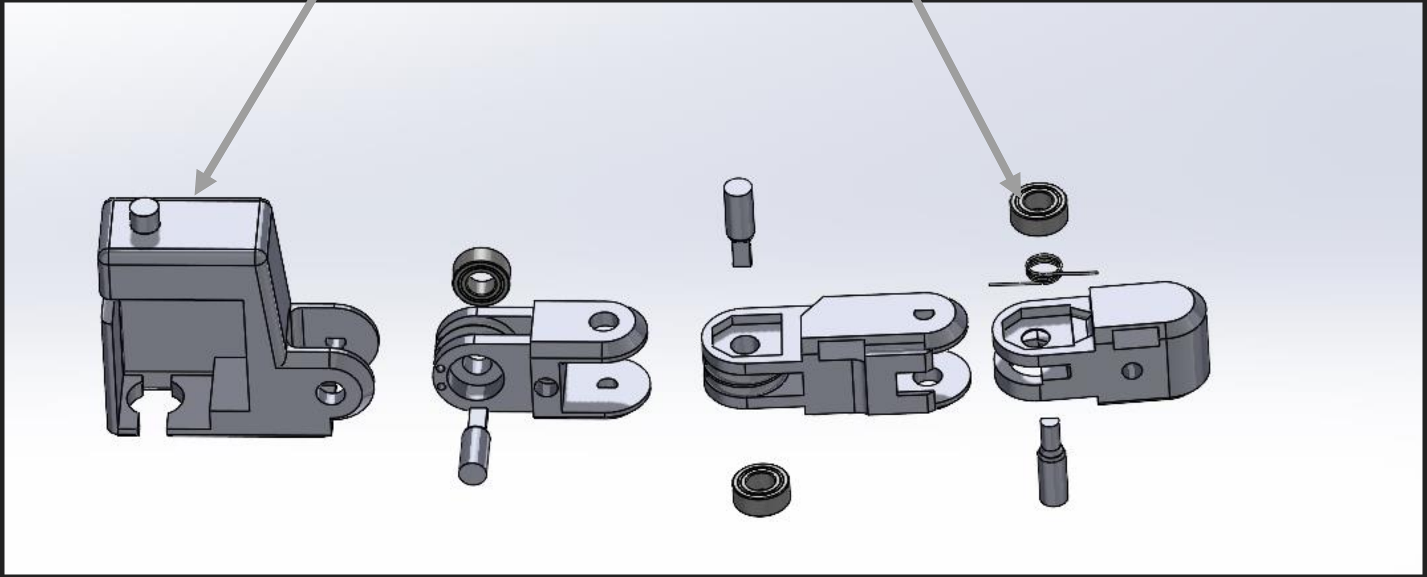
Spring for extension



Final Hardware: Thumb

Servo placement

Spring for extension



Final Testing - Top Level Testing Summary Table

Experiment/ Test	Relevant Design Requirements
T1 - Static Grip Strength	CR1, ER1
T2 - Actuation Speed Test	CR2, ER2
T3 - Weight and Size Test	CR3, CR4, ER3, ER4
T4 - Durability and Thermal Release	CR8, C10, ER8, ER10
T5 - Sensor Accuracy Calibration	CR11, ER11
T6 - Power Draw Test	CR7, ER7
T7 - User Interface Evaluation	CR9, ER9
T8 - Functional Performance Test	CR1, CR2, CR11, ER1, ER2, E11
T9 - Degrees of Freedom and Budget Evaluation	CR5, CR6, ER5, ER6

Final Testing - Specification Sheet (CRs)

Customer Requirement	CR met? (yes or no)	Client Acceptable (yes or no)
CR1 - Strong enough to play piano and catch a ball	No	No
CR2 - Fast enough to play piano and catch a ball	yes	Yes for ball, no for piano
CR3 - Accurate dimensions	yes	yes
CR4 - Accurate weight	yes	yes
CR5 - Within budget	yes	yes
CR6 - Many degrees of freedom	yes	yes
CR7 - Uses standard form of power	yes	Yes
CR8 - Does not overheat	yes	Yes
CR9 - Has a basic and functional UI	yes	Yes (75% agree)
CR10 - Reliable	yes	Yes (75% agree)
CR11 - Precision of motion	No	No

Final Testing - Specification Sheet (ERs)

Engineering Requirement	Target	Tolerance	Measured/ Calculated Value	ER met? (yes or no)	Client Acceptable (yes or no)
ER1 - Grip Force	45-50 N	5 N	16-19.6 N	No	Yes
ER2 - Full extension to full closure	200-250 ms	25 ms	125 ms	Yes	yes
ER3 - Scale of human dimensions	1-1.5x	N/a	0.79-2.22 times (1.3 AVG)	Yes	Yes
ER4 - Accurate weight	3-4kg	0.3 kg	1.76 kg	Yes	Yes
ER5 - Within budget	<$1500	N/a	$1,162	yes	yes
ER6 - Degrees of freedom	15 DOF	1 DOF	15	yes	yes
ER7 - Operates with 1 - 3 standard 120V plugs	1-3 Plugs 360 W	0 50 W	1 plug 60 - 180 W	yes	yes
ER8 - Does not overheat	<75°C	5°C	58.5°C	yes	yes
ER9 - Easy to use	⅘ score on qualitative survey	N/a	4/5	yes	yes
ER10 - Reliable use	> 10,000 joint cycles	N/a	13,681	yes	yes
ER11 - Accuracy of finger	Within 5 mm	N/a	20 mm at tip	no	no

Future Work

- Improve code so hand has a better and simpler movement controls
- Implement the Raspberry Pi more so all communication goes through the Pi to talk to the other electronics.

Acknowledgements

- Carson Pete
- Reza Razavian
- Zach Lerner

Thank You

Appendix

- Spring info?