Humanoid Hand

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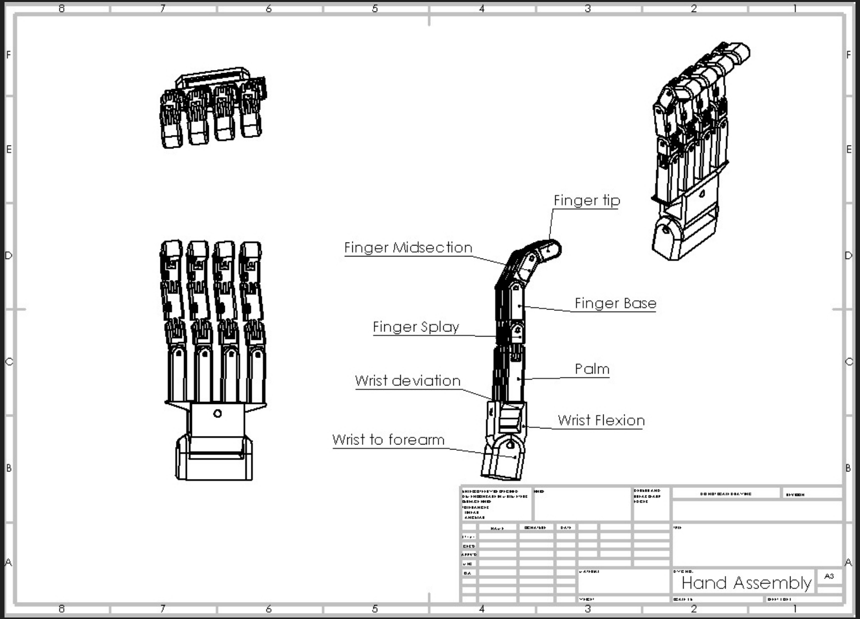
Project Description

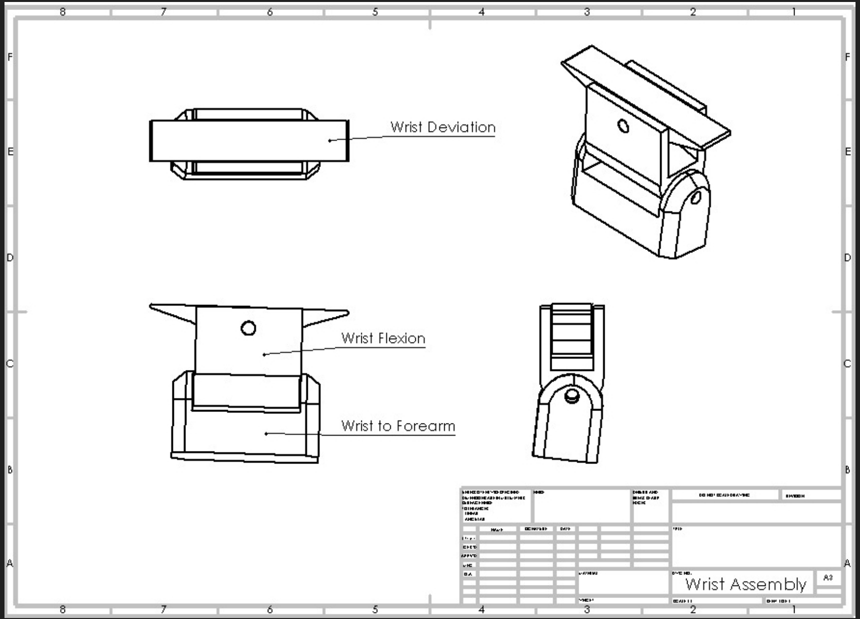
A robotic hand that matches the capabilities of the human hand

Finishing finger design and beginning thumb and wrist design

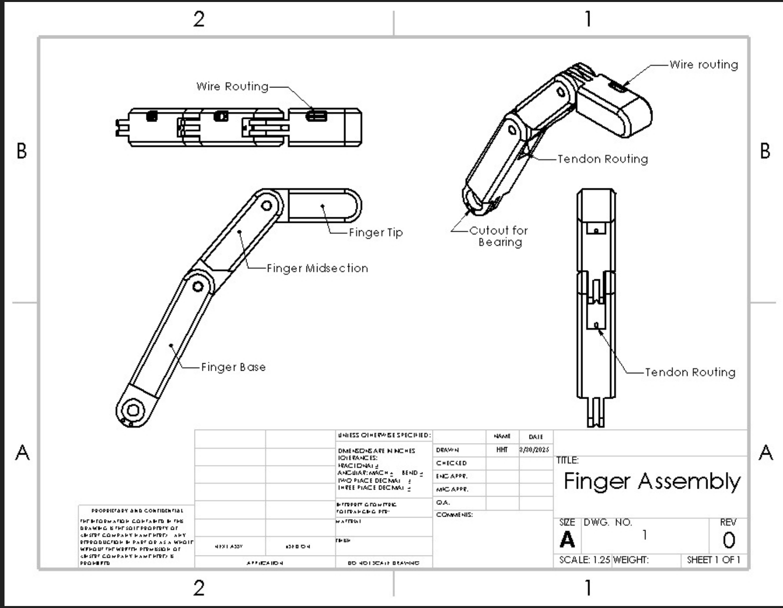
Sponsored by:
Dr. Zach Lerner
Dr. Reza Razavian

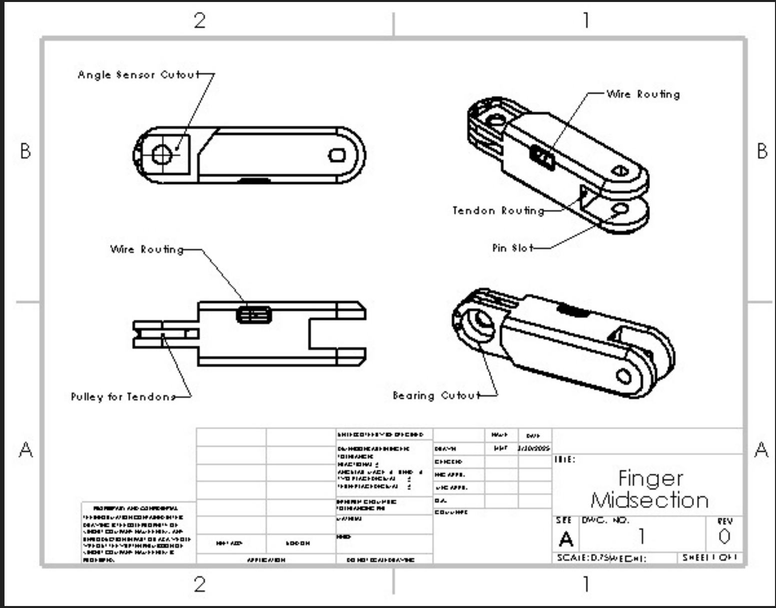
Design Description





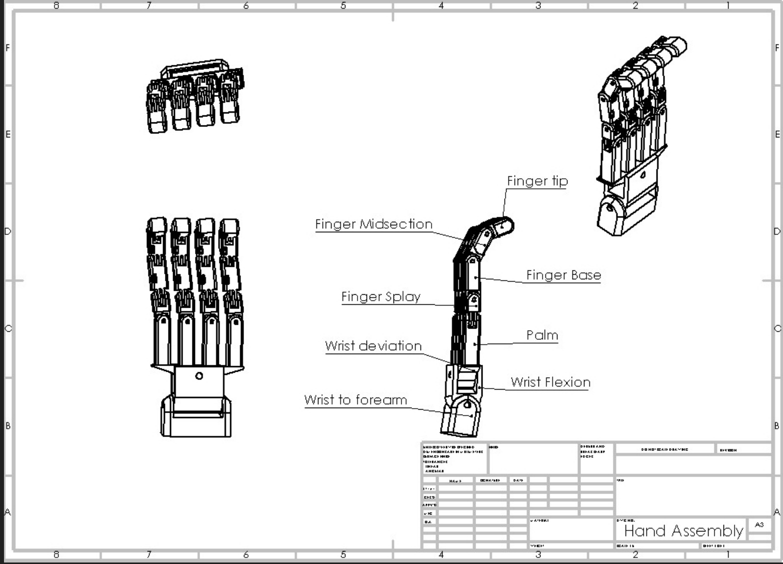
Design Description





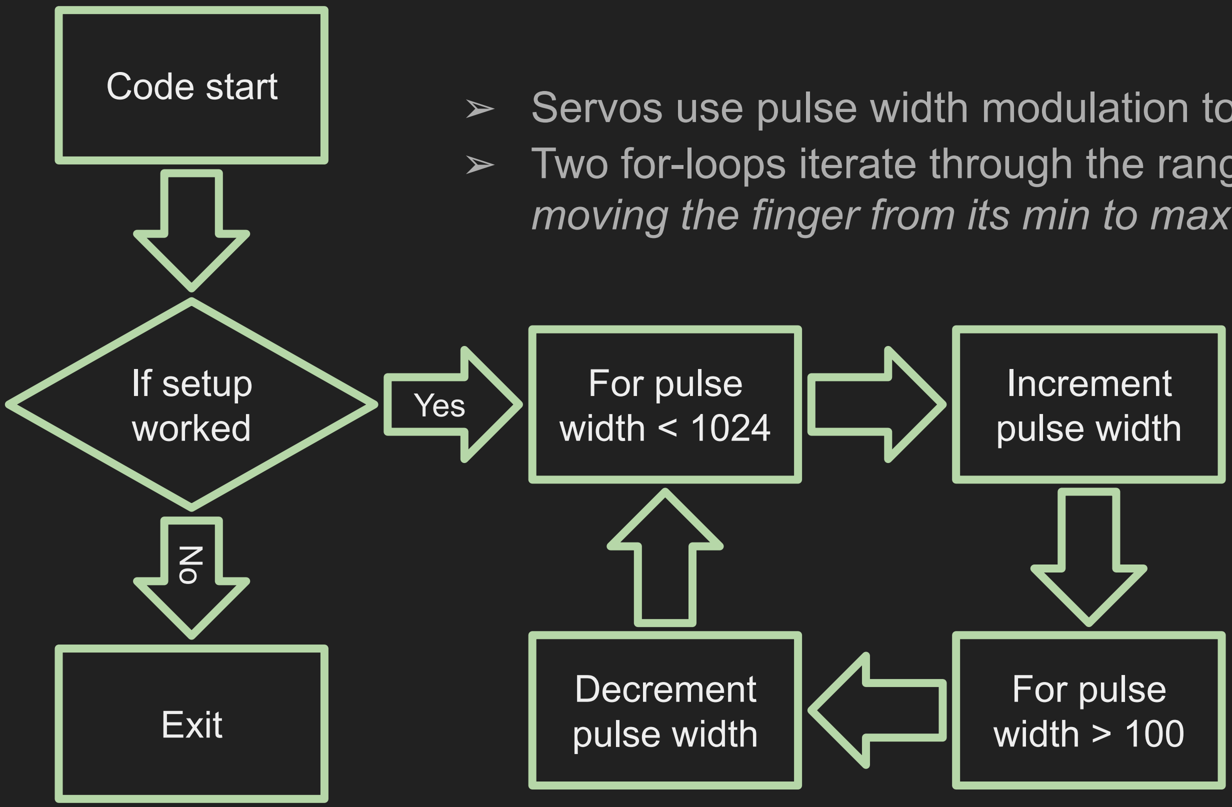
Design Description

- Uses motors to pull a tendon for actuation
- Each joint only allows for one DOF
- So 2 joints to replace a single joint in hand
    - Ie one for flexion and one for deviation in the wrist
- Finger subsystem attaches to wrist through palm extension coming from “Wrist Deviation”
- Thumb (not pictured) will attach in front of palm extension and operate similarly to other fingers



Control Theory

- Servos use pulse width modulation to specify angular position.
- Two for-loops iterate through the range of pulse width values, *moving the finger from its min to max position.*



Control Theory

- This control scheme serves only as proof-of-concept for servo control.
  - We will have “nested” control.
- Example:
  - Grasp object function calls the move finger functions, specifying desired angular positions.
    - Each move finger function uses PWM to move the finger’s motor to the desired angular position specified by grasp object.
- This affords us much modularity.

Customer Requirements

- Strength
- Speed
- Accurate Dimensions
- Accurate Weight
- Budget
- Many Degrees of Freedom
- Standard Form of Power to Function
- Basic Functional UI
- Precise Motion

Engineering Requirements

- Grip force (120-160N)
- Extension/Closure time (250-350ms)
- Approximate Size (1-1.5X)
- Approximate Weight (1-1.5X)
- Manufacturing Cost ($1500)
- Degrees of Freedom (20 Deg)
- Ease of operation (10-20min start)
- Cycles (10K)
- Positional Accuracy (+/- .5mm)

QFD

Customer Needs	Customer Weights(1-5)	Technical Requirements: Grip Force between 120-160N	Time from full extension to full closure is 250-350ms	Approximate size of human hand	Apx 3-4kg	Cost of manufacturing<$1500	apx 20 DOF	Can be opperated by Lerner or Reza with a <10min demo	Each joint ensured up to 10k motions	Able to predict finger segment placement within +/- 5mm based sensor data	Customer Opinion Survey: 1 *Poor*	2	3 *Acceptable*	4	5 *Excellent*
Strength	3	9	3	3	3	9	9	3	9	3		B		C	A
Speed	5	3	9	3	1	9	9	3	9	9			C	B	A
Accurate dimensions	2	3	3	9	9	3	9	3	9	3			A	C	B
Accurate weight	1	9	9	9	9	3	3	3	9	9		A	C		B
Budget	4	9	3	3	9	9	3	9	9	9	A		C		B
Many degrees of freedom	4	3	3	3	3	9	9	9	9	3	C			B	A
Uses stand form of power to function	5	1	1	9	9	9	1	9	3	3					ABC
Has basic and functional ui	4	1	1	1	3	3	3	9	1	9	C			B	A
Precision of motion	4	3	3	9	3	9	3	9	9	9			B		AC
Technical Requirement Units		N	s	s	kg	$	deg	min	#	mm					
Technical Requirement Targets		160	0.3	250	4	150	20	10	10k	5					
Absolute Technical Importance		126	114	160	158	246	170	222	226	204					
Relative Technical Importance		8	9	6	7	1	5	3	2	4					

Legend:

A	Shadow Hand
B	Dex Hand
C	Optimus Hand

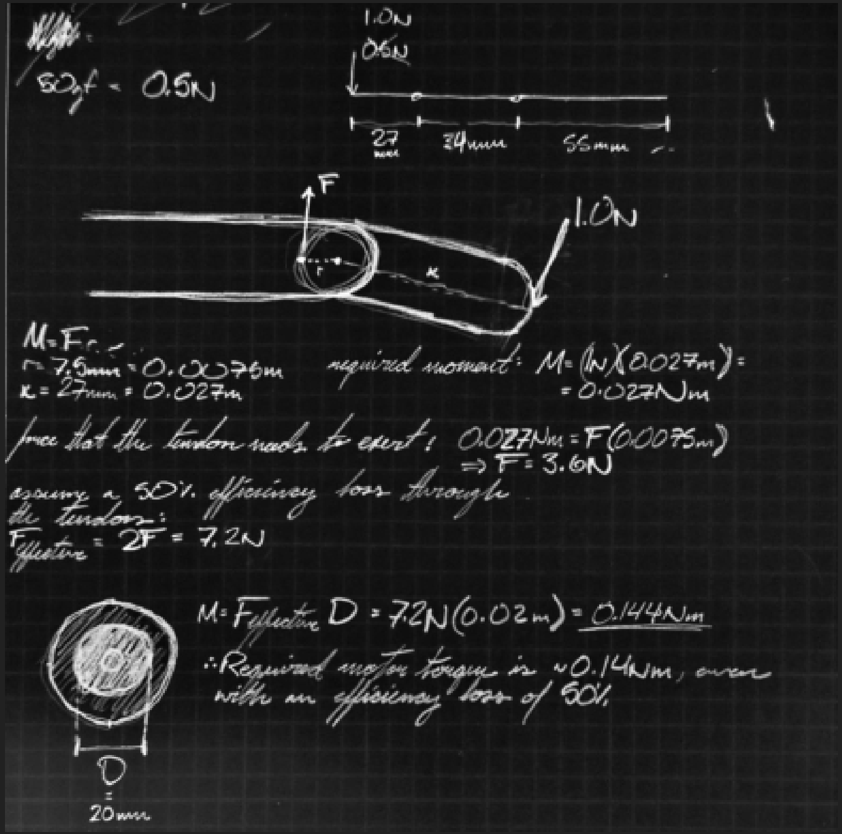
Engineering Calculations

Motor Torque Analysis

<u>Need</u>: Press a piano key.

With a rudimentary statics analysis, and accounting for a 50% loss in efficiency through the tendons, <u>required motor torque is 0.144Nm.</u>

A very attainable value.



3R Planar Manipulator Velocity Vector

Taking time derivative of forward kinematics equation and converting to matrix form yields:

$$\begin{bmatrix} -L_1\sin(\theta_1) - L_2\sin(\theta_1+\theta_2) - L_3\sin(\theta_1+\theta_2+\theta_3) & -L_2\sin(\theta_1+\theta_2) - L_3\sin(\theta_1+\theta_2+\theta_3) & -L_3\sin(\theta_1+\theta_2+\theta_3) \\ L_1\cos(\theta_1) + L_2\cos(\theta_1+\theta_2) + L_3\cos(\theta_1+\theta_2+\theta_3) & L_2\cos(\theta_1+\theta_2) + L_3\cos(\theta_1+\theta_2+\theta_3) & L_3\cos(\theta_1+\theta_2+\theta_3) \end{bmatrix} \begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \\ \dot{\theta}_3 \end{bmatrix} = \begin{bmatrix} \dot{x} \\ \dot{y} \end{bmatrix}$$

For lengths from previous analysis and example angles and velocities:

$$L_1 = 8.7884\,\text{cm}, L_2 = 4.9784\,\text{cm}, L_3 = 4.2672\,\text{cm}$$

$$\theta_1 = 56^\circ, \theta_2 = -28^\circ, \theta_3 = -10^\circ$$

$$\dot{\theta}_1 = 30^\circ/\text{s}, \dot{\theta}_2 = 10^\circ/\text{s}, \dot{\theta}_3 = -10^\circ/\text{s}$$

$$\begin{bmatrix} \dot{x} \\ \dot{y} \end{bmatrix} = \begin{bmatrix} -6.1369\,\text{cm/s} \\ 7.7667\,\text{cm/s} \end{bmatrix}$$

This equation can be iteratively solved for the velocity vector of the fingertips

Gear Teeth and Speed Calc

Gear Ratio of 2:1

- Higher torque, more precise, slower movement.
- Gear teeth are 40 and 20 teeth

Input Speed of 278 RPM (from a previous calculation)

$$GR = \frac{\text{Output Speed}(\omega_o)}{\text{Input Speed}(\omega_i)}$$

$$GR = \frac{Z_o}{Z_i}$$

$$\omega_o = \frac{278}{2} = 139 \text{ RPM}$$

Tendon Pulley Analysis

Tendon Material: PBO
Young's Modulus: 270 GPa
S(ut): 5800 MPa
Se': 2900 MPa
F-max = 40N
Tendon Diameter: 0.25mm

Tension Stress:

$$\sigma_{\text{tension}} = \frac{40\,\text{N}}{0.049\,\text{mm}^2} = 816\,\text{MPa}$$

Bending Stress:

$$\sigma_{\text{bend}} = 270,000 \cdot \frac{0.25}{25} = 2,700\,\text{MPa}$$

Pulley Diameter:

$$D \geq 0.25 \cdot \frac{270,000 \times 2}{5,800} = 0.25 \times 93.1 = 23.3\,\text{mm}$$

Cross Sectional Area:

$$A = \frac{\pi}{4} \times (0.25)^2 = 0.049\,\text{mm}^2$$

Total Stress:

$$\sigma_{\text{total}} = 816 + 2,700 = 3,516\,\text{MPa}$$

Stress ratio:

$$\frac{3{,}516}{2{,}900} = 1.21 \rightarrow \sim 10^4 \text{ cycles}$$

Forward Kinematics of a 3-Link Finger with Splaying Motion

Givens:

- $L_1 = 3.46$ in, $L_2 = 1.96$ in, $L_3 = 1.68$ in
- $\theta_1 = 0°, \theta_2 = -90°, \theta_3 = -45°, \phi = 15°$

First Joint:

$$x_1 = L_1 \cos(\theta_1) = 3.46 \cos(0) = 3.46$$

$$y_1 = L_1 \sin(\theta_1) = 3.46 \sin(0) = 0$$

$$z_1 = 0$$

Second Joint:

$$x_2 = x_1 + L_2 \cos(\theta_1 + \theta_2) = 3.46 + 1.96 \cos(-90) = 3.46$$

$$y_2 = y_1 + L_2 \sin(\theta_1 + \theta_2) = 0 + 1.96 \sin(-90) = -1.96$$

$$z_2 = 0$$

End Effector:

$$x_3 = x_2 + L_3 \cos(\theta_1 + \theta_2 + \theta_3) \cos(\phi)$$

$$= 3.46 + 1.68 \cos(-135) \cos(15) = 2.314$$

$$y_3 = y_2 + L_3 \sin(\theta_1 + \theta_2 + \theta_3) \cos(\phi)$$

$$= -1.96 + 1.68 \sin(-135) \cos(15) = -3.106$$

$$z_3 = z_2 + L_3 \sin(\phi) = 1.68 \sin(15) = 0.435$$

Final Position:

$$(x_3, y_3, z_3) = (2.314, -3.106, 0.435)$$

Pin Shear Stress Recalculation

- Shear force is sum of F_t+F_g
  - F_t is from tendon
  - F_g is external load at fingertip
- F_t is a result of the torque at a given joint and the length of the moment arm
- Shear stress is a result of shear force divided by cross sectional area
- Smallest cross sectional area as determined by Solidworks
- Final expanded shear stress equation in terms of torque, radius of moment arm, force at fingertip, and diameter of joint

$$V = F_t + F_g$$

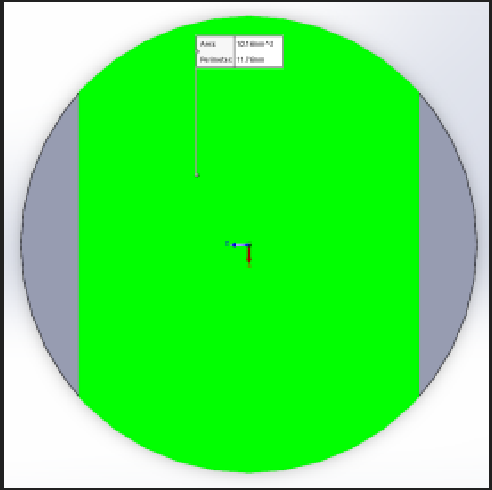
$$F_t = \frac{T}{r}$$

$$\tau = \frac{V}{A}$$

$$\tau = \frac{\left(\frac{T}{r} + F_g\right)}{lw}$$

Shear Stresses on Joints cont.

- F_g from forces in finger distribution (pres 1)
  - Clients are less interested in strength so forces are halved



$$\tau = \frac{\left(\frac{T}{r} + F_g\right)}{lw}$$

Joint	Torque (T) (Nm)	Shear Force V (N)	Shear Stress τ (MPa)
Thumb 1	2.225	266.975	26.28
Thumb 2	1.335	177.975	17.52
Thumb 3	0.665	110.975	10.92

- Max shear is apx 26 MPA
  - Carbon fiber has similar shear strength

Calculation Table

Table 5: Summary of calculations

Calculation	*Equation(s)*	*Application*	*Requirement Met*	*Validation*
Projectile motion	$x_f = x_0 + v_{0x}t$ $x_f = (v^2 sin2theta)/g$	*Catching a ball*	*Dexterity and reaction speed*	*Dynamics* *Assumptions*
Finger tip joint inference	$theta_{Tip} = .667theta_{Mid}$ $theta_{Tip} = .556theta_{Mid}$ $theta_{Tip} = .333theta_{Mid}$	*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*
Finger tip location (x,y)	$x = L_1 \cos\theta_1 + L_2 \cos(\theta_1 + \theta_2)$ $y = L_1 \sin\theta_1 + L_2 \sin(\theta_1 + \theta_2)$	*Finding location of fingertip in terms of the base joint*	*Control of the fingers*	*Implementing code* *Real finger lengths*
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, EE188* *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*

Design Validation

Most critical components are servos, motors, and angle sensors, according to the RPN values:

Part # and Functions	Potential Failure Mode	Potential Effect(s) of Failure	Potential Causes and Mechanisms of Failure	RPN	Recommended Action
1 Fingers/Frame	Force-induced deformation Impact deformation	Breaking of fingers and frame	Overstressing, high impact loads	36	Select strong material
2 Bearings	High-cycle Fatigue Temp-induced deformation	High friction, inaccurate actuation	Inadequate venting, cyclic failure	60	Choose appropriate commercial bearings or explore bushing joints
3 Pulleys	High-cycle Fatigue Force-induced deformation	Moderate to severe inability of actuation	High impact loads, cyclic failure	36	Select or machine strong pulleys
4 Tendon Cord	Ductile Rupture	Inability of operation	Inadequate routing, high stress loads	147	Select a strong but flexible tendon cord
5 Tendon Housing	Abrasive wear	Lack of protection for tendon cords	Inadequate routing, cyclic failure	50	Ensure flexibility in cable housing
6 Servos	High-cycle Fatigue	Limited DoF	Suboptimal power supply, cyclic failure, faulty wiring	252	Select high quality servos
7 Motors	High-cycle Fatigue	Moderate to severe inability of actuation	Suboptimal power supply, cyclic failure, faulty wiring	294	Select high quality motors
8 Angle Sensors	Force-induced deformation	Inability to interface	High impact loads, faulty wiring, noisy signal	336	Select accurate and high quality angle sensor

Failure mitigated by selection of high quality components

Cable housing greatly reduces possibility of tendon cord ductile failure

Testing Overview

Engineering Requirement	Units	Target	Tol.	Tests
Grip Force	N	120-160	20	Have the hand statically hold dumbbells of increasing weight from 5-25 lbs based on analysis of strength
Grip Speed	ms	250-350	50	Time for 10 complete extensions and closures
Size of Average hand/forearm	cm^3	1200	400	Volume analysis in solidworks
Weight of average hand/forearm	kg	3.5	1	Weighing apparatus on scale
Cost of Manufacturing	$	1500	250	Total price of each part in final design
Many DOF	#	20	1	Count DOF in final design
Easy to power	V	120	0	Plug into wall outlet and operate
Easy to use interface	min	10	5	Teach each client individually and time how long until they are confident to run and test independent of instructor
Precise and Accurate Motion	mm	1	.5	Pick positions in 3d space and determine accuracy. Play the piano
Longevity	#	10,000	250	Use a single finger to fully close and open until it fails

Schedule

TASK	ASSIGNED TO	PROGRESS	START	END	EST. HOURS	ACTUAL HOURS
Phase 1 (1st Prototype Demo)						
Work on Presentation 1	Team	100%	1/27/25	2/10/25	10.00	20.00
Establish Finger Design	Team	100%	2/4/25	2/18/25	30.00	40.00
Establish Control Scheme	Joseph, Noah	100%	2/4/25	2/18/25	10.00	20.00
Order Preliminary Parts	Justin	75%	2/18/25	2/21/25	1.00	
Presentation 2	Team	100%	2/18/25	3/2/25	10.00	40.00
Joint Prototype	Team	100%	2/18/25	3/31/25	40.00	50.00
Phase 2 (Phalange Prototype)						
Report 1	Team	100%	3/1/25	3/9/25	30.00	40.00
Website Check 1	David, Markus	100%	2/25/25	3/9/25	10.00	25.00
Analysis Memo	Team	100%	3/1/25	3/21/25	20.00	30.00
Presentation 3	Team	100%	3/9/25	3/31/25	10.00	50.00
Finger Prototype	Team	95%	2/18/25	3/31/25	60.00	
1st Prototype Demo	Team	100%	2/1/25	3/31/25	5.00	20.00
Phase 3 (Whole Hand)						
Report 2	Team	0%	4/1/25	4/18/25	20.00	
Final CAD and Final BOM	Tyler, Noah	0%	4/1/25	4/25/25	10.00	
2nd Prototype Demo	Team	0%	4/1/25	4/28/25	5.00	
Website Check 2	David, Markus	0%	4/1/25	5/4/25	10.00	
Whole hand Prototype	Team	0%	4/1/25	4/31/25	60.00	

Schedule

Phase 4 (Startup of 486C)					
Project Management for 486C	Team	0%	4/1/25	5/2/25	10.00
Project Management	Team	0%	8/28/25	8/30/25	10.00
Engineeering Calculations	Team	0%	8/28/25	9/4/25	10.00
Double check Prototype and adjust	Team	0%	8/28/25	9/31/25	30.00
Phase 5 (Building)					
Hardware Status Update - 33%	Team	0%	8/28/25	9/25/25	60.00
Hardware Status Update - 67%	Team	0%	8/28/25	10/16/25	60.00
Hardware Status Update - 100%	Team	0%	8/28/25	11/6/25	60.00
Phase 6 (Collection of Stuff)					
Website Check 3	David, Markus	0%	8/28/25	10/9/25	10.00
Finalized Testing plan	Team	0%	10/16/25	10/30/25	10.00
Final CAD Packet	Team	0%	11/1/25	11/20/25	5.00
Final Report & Final Website check	Team	0%	11/1/25	11/27/25	30.00

Phase 7 (E-Fest)					
UGrads registration	Team	0%	10/23/25	10/24/25	1.00
Draft of poster	Team	0%	10/1/25	10/30/25	15.00
Final Poster & PPT	Team	0%	11/1/25	11/13/25	20.00
Presentation	Team	0%	12/8/25	12/8/25	5.00
Conclusion					
Initial Testing Results Video	Team	0%	11/6/25	11/20/25	5.00
Product demo	Team	0%	11/6/25	11/27/25	5.00
Client Handoff	Team	0%	12/11/25	12/11/25	1.00

Budget

	Budget Robotic Hand							
	Total Budget							$2,000
Item #	Item	Description	Planned Aquisiton Date	Actual Acquisiton Date	Price Per Unit	# of Units	Estimated Total Price	Actual Total Price
1	Motors	Motor with AS5048A Encoder	4/14/2025		$42.97	8	$343.76	
2	Motors	INJORA INJS035 35KG	4/14/2025		$16.99	6	$101.94	
	Breadboard	4PCS breadboard kit	4/14/2025		$6.78	1	$6.78	
	Wiring	22 guague Silicon wire	4/14/2025		$19.13	1	$19.13	
	Potentiameter	Angle sensors	4/14/2025		$1.34	20	$33.55	
3	Filament	PLA Prototyping Filament	4/14/2025		$14.99	1	$14.99	
5	Filament	Onyx Filament	4/14/2025		$209	1	$209	
6	Filament	50cc Carbon Fiber Spool	4/14/2025		$150	1	$150	
7	Computation	Arduino Mega	4/14/2025		$49.65	1	$49.65	
8	Actuation	Dyneema Cord	4/14/2025		$32.99	1	$32.99	
9	Actuation	Bearings	4/14/2025		$7.17	15	$107.55	
	Estimated Remaining Budget							$930.66
	Actual Remaining budget							$2,000

Virtual Prototype

A MATLAB code was implemented to simulate 3-Link forward kinematics

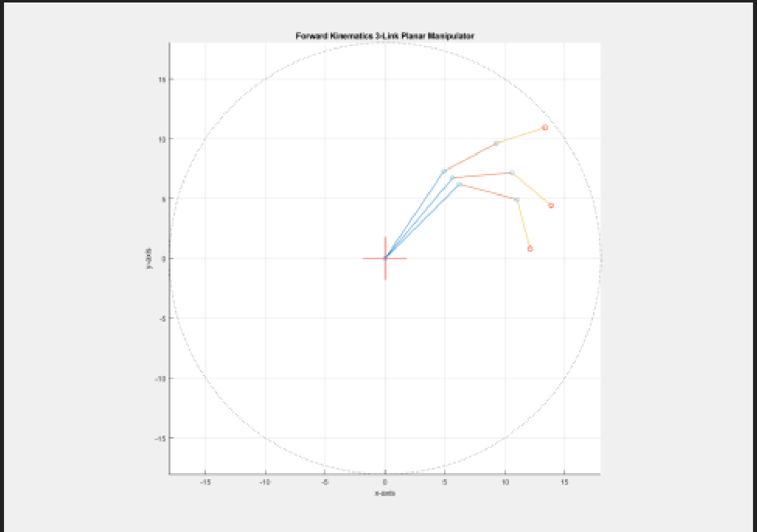
The script utilizes a function to take 6 inputs: L1, L2, L3, theta1, theta2, and theta3

Using lengths and angles from previous analyses, the outputs are show below for different angles:

```
>> fkinematics(8.7884, 4.9784, 4.2672, 56, -28, -10)
The position of the end-effector is (13.368426, 10.941768) and orientation is(18.000000)
>> fkinematics(8.7884, 4.9784, 4.2672, 50, -45, -45)
The position of the end-effector is (13.877395, 4.423298) and orientation is(-40.000000)
>> fkinematics(8.7884, 4.9784, 4.2672, 45, -60, -60)
The position of the end-effector is (12.127535, 0.804034) and orientation is(-75.000000)
```

Virtual Prototype

The outputs for each input are shown below in a graph:



This virtual prototype informs the design and data collection of the interface software

Physical Prototype

- How does it function?
  - Raspberry Pi uses the control flow mentioned previously to sweep through the range of motion
  - The sweep is performed by gradually increasing and decreasing the pulse width

References

[1] juecoreein S. • 3 years ago, “Forward and Reverse Kinematics for 3R Planar Manipulator,” Hive, Dec. 21, 2020. https://hive.blog/hive-196387/@juecoree/forward-and-reverse-kinematics-for-3r-planar-manipulator (accessed Mar. 31, 2025).