Humanoid Hand

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Project Description

A robotic hand that matches the capabilities of the human hand

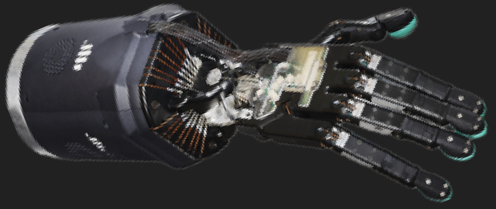
Sponsored by:
Dr. Zach Lerner
Dr. Reza Razavian

[1]

Background and Benchmarking

Shadow Hand:

- Highly accurate, hall effect sensors in every joint
- 24 DoF
- 20 motors
- Tactile Sensing



[2]

DexHand:

- Open-source, lots of documentation
- Low cost
- Teleoperation

[3]

Tesla Optimus:

- 22 Dof
- 6 Motors
- Underactuated
- Tactile sensing

[4]

Customer and Engineering Requirements

Customer Requirements

- Be as close as possible to human hand
- Average size and weight of human hand
- Have the average force capacity of an adult
- High repeatability in joints
- Within reasonable budget
- Basic and functional UI

Engineering requirements

- Grip force 25-40kg
- Time from open to closed hand 150-300ms
- Apx Size of human hand
- Entire contraption weighs 2.5-3kg
- Cost of manufacturing<$1500
- Approximately 20 DOF
- Can be operated by clients with less than a 10 min demo
- Each joint can be actuated 10,000 times

Quality Function Deployment

		Technical Requirements										Customer Opinion Survey				
Customer Needs	Customer Weights(1-5)	Grip Force between 240-390N	Time from full extenstion to full closure is 150-300ms	Approximate size of human hand	Apx 2.5-3kg	Cost of manufacturing<$1500	apx 20 DOF	Can be opperated by Lerner or Reza with a <10min dem	Each joint ensured up to 10k motions			1 Poor	2	3 Acceptable	4	5 Excellent
Strength	5	9	3	3	3	9	9	3	9				B		C	A
Speed	4	3	9	3	1	9	9	3	9					C	B	A
Accurate dimensions	3	3	3	9	9	3	9	3	9					A	C	B
Accurate weight	2	9	9	9	9	3	3	3	3				A	C		B
Budget	4	9	3	3	9	9	3	9	9			A		C		B
Many degrees of freedom	4	3	3	3	3	3	9	9	9			C			B	A
Uses stand for of power to function	5	1	1	9	9	9	1	9	3							ABC
Has basic and functional ui	4	1	1	1	3	3	3	9	1			C			B	A
Technical Requirement Units		N	s	s	kg	$	deg	min	#							
Technical Requirement Targets		390	0.3		3	150	20	10	10k							
Absolute Technical Importance		141	111	145	169	201	179	195	205							
Relative Technical Importance		7	8	6	5	2	4	3	1							

Legend:

A	Shadow Hand
B	Dex Hand
C	Optimus Hand

Justin’s Literature Review

Books:

- Fundamentals of C++ programming [28]
- Programming Fundamentals - A Modular Structured Approach using C++ [27]

Journal articles :

- Integrated linkage-driven dexterous anthropomorphic robotic hand [9]
- Design of a Highly Biomimetic Anthropomorphic Robotic Hand towards Artificial Limb Regeneratior [12]
- Finger Kinematics during Human Hand Grip and Release - PMC [10]
- *Design of Tendon-Driven Robotic Fingers: Modeling and Control Issues*.[8]

Websites:

- Advanced Humanoid Robotic Hand Technologies | T2 Porta [7]
- Servos Explained [11]

Noah’s Literature Review

Books:

- “Practical Robotics in C++” [17]
- “The C++ Programming Language” [18]

Journal Articles:

- “A review of Robot Learning for Manipulation” [19]
- “On Dexterity and Dexterous Manipulation” [20]
- “Postural Hand Synergies for Tool Use” [21]

Websites:

- “robotnanohand.com” [22]
- Github repository for C++ functions useful for robotics programming [23]

Tyler’s Literature Review

Books:

- Kinematic modelling of the human hand for robotics [29]
- Human Hand Function [30]

Journal Articles:

- Functional Anatomy and Biomechanical Concepts in the Hand [31]
- Biomechanics of the Human Hand [32]
- Biomechanical Characteristics of Hand Coordination in Grasping Activities of Daily Living [34]

Websites:

- Biomechanics of the Hand [33]

Literature covers the individual and complex movement of the human hand, how the hand moves and grips items.

David’s Literature Review

Books:

Robot Arm Kinematics[25]

Simply Grasping Simple Shapes[26]

Journal Articles:

Design and control of robotic hands[13]

Mechanical design of a biologically inspired prosthetic hand, The Touch hand 3 [14]

Put-hand-hybrid industrial and Biomimetic Gripper for Elastic Object Manipulation [15]

- All are different hand/ finger design

Performance optimizing of pneumatic soft robotic hands using wave-shaped contour actuator [16]

- Pneumatic finger design
- All silicon/rubber material

Websites:

National Robotics Educational Foundation (the-nref.com)

Joseph's Literature Review

Books:

- Arduino Robotics [37]
- Theory of Applied Robotics: Kinematics, Dynamics, and Control (3rd Edition) [38]
- Modern Robotics: Mechanics, Planning, and Control [39]

Journal Articles:

- Robust Feedback Control Design of Underactuated Robotic Hands with Selectively Lockable Switches for Amputees [40]
- Modern C++ as a Modeling Language for Automated Driving and Human-Robot Collaboration [41]

Websites:

- Packt Publishing: Hands On Robotics Programming with Cpp [42]
- Raspberry Pi Settings for Robotics [43]

Markus’ Literature Review

Books:

- InformedHealth.org. Cologne, Germany: Institute for Quality and Efficiency in Health Care (IQWiG); 2006-. In brief: How do hands work? [Updated 2021 May 20] https://www.ncbi.nlm.nih.gov/books/NBK279362/[44]
- P. W. Brand and A. Hollister, *Clinical Mechanics of the Hand*. St. Louis: Mosby Year Book, 1993. [45]

Journal Articles:

- E. Nazma and S. Mohd, “ TENDON DRIVEN ROBOTIC HANDS: A REVIEW,” *International Journal of Mechanical Engineering and robotics research*. doi:10.18178/ijmerr [46]
- Zhe Xu and E. Todorov, “Design of a highly biomimetic anthropomorphic robotic hand towards artificial limb regeneration,” *2016 IEEE International Conference on Robotics and Automation (ICRA)*, pp. 3485–3492, May 2016. doi:10.1109/icra.2016.7487528 [47]
- Zhe Xu, V. Kumar, and E. Todorov, “A low-cost and modular, 20-DOF anthropomorphic robotic hand: Design, actuation and modeling,” *2013 13th IEEE-RAS International Conference on Humanoid Robots (Humanoids)*, pp. 368–375, Oct. 2013. doi:10.1109/humanoids.2013.7030001 [48]

Websites:

- “Bionicsofthand,” BionicSoftHand | Festo USA, https://www.festo.com/us/en/e/about-festo/research-and-development/bionic-learning-network/highlights-from-2015-to-2017/bionicsofthand-id_68106/ (accessed Feb. 9, 2025).[49]

Mathematical Modeling

Mathematical Modelling: Power Analysis

Need: Adaptable method to calculate power consumption

Solution: Python script

Max Power Draw:

~107 Watts

```python
# ~~~~~~~~~~~~~~~~~~~~~~ Create an object for the hand ~~~~~~~~~~~~~~~~~~~~~~ #
class RoboticHand:  1 usage
    def __init__(self, motors, control_circuits):
        self.motors = motors
        self.control_circuits = control_circuits

    def total_power_consumption(self, is_active=False):  1 usage
        # Sum power consumption of all motors:
        motor_power = sum(motor.power_consumption() for motor in self.motors)

        # Sum power consumption of control circuit components:
        circuit_power = sum(control_circuit.power_consumption() for control_circuit in self.control_circuits)

        # Total power consumption:
        return motor_power + circuit_power

# ~~~~~~~~~~~~~~~~~~~~~~~ Instantiate the robotic hand ~~~~~~~~~~~~~~~~~~~~~~~ #
robotic_hand = RoboticHand(
    motors=[index_motor1, index_motor2, middle_motor1, middle_motor2, ring_motor1,
            ring_motor2, pinky_motor1, pinky_motor2, thumb_motor1, thumb_motor2,
            thumb_motor3],
    control_circuits=[raspberry_pi, arduino_nano]
    )

# Calculate total power consumption:
total_power = robotic_hand.total_power_consumption(is_active=False)
```

Mathematical Modelling: Power Analysis (Cont.)

Structure:

- Classes for each type of component (motor, microcontroller, etc.)
  - Those classes have attributes such as operating voltage and current draw.
- Objects representing each particular component inherit those classes.
- Objects take on values unique to the thing they represent (this motor draws this much current).
- A class representing the whole hand takes all of those objects in as arguments and calculates the total power consumption.

Mathematical Modeling: Projectile Motion and Reaction Speed

To calculate the reaction speed of the robotic hand, projectile motion equations can be used:

$$x_f = x_0 + v_{0x} t \quad \text{(eq 1)}$$

$$x_f = \frac{v_0^2 \sin 2\theta}{g} \quad \text{(eq 2)}$$

These equations can be used to solve for the flight time of an object at certain conditions assuming level ground, ideal launch angle, and ideal horizontal distance.

Mathematical Modeling: Projectile Motion and Reaction Speed Cont.

Using equation 2, and assuming ideal conditions of a launch angle of 30 degrees and a horizontal distance of 1.5 meters, equation 2 becomes:

$$1.5m = \frac{v_0^2(2\sin 30\cos 30)}{9.81m/s^2}$$

Initial velocity is solved to be 4.122 meters per second. Plugging this value into equation 1:

$$1.5m = 0 + [(4.122m/s)cos30]t$$

Solving for t yields a time of .42 seconds, which means the code will need to run at .42 cycles per second, or .42 hertz, to have enough reaction time.

Mathematical Modeling: Forces In fingers

The average grip force of a person is 80 lbs and that is the maximum force that will be applied distributed based on average percent weight distribution.

Thumb force $F_{\text{thumb}} = 0.25 \times 355.8\,\text{N} = 88.95\,\text{N}$

Index force $F_{\text{index}} = 0.30 \times 355.8\,\text{N} = 106.74\,\text{N}$

Middle force $F_{\text{middle}} = 0.15 \times 355.8\,\text{N} = 53.37\,\text{N}$

Ring force $F_{\text{ring}} = 0.15 \times 355.8\,\text{N} = 53.37\,\text{N}$

Pinky force $F_{\text{pinky}} = 0.10 \times 355.8\,\text{N} = 35.58\,\text{N}$

Torques on the fingers assuming 1 cm distance from joints and same length of all fingers(except thumb)

A. Thumb:

$\tau_{\text{thumb, joint 1}} = 88.95 \cdot 0.05 = 4.45\,\text{N}\cdot\text{m}, \quad \tau_{\text{thumb, joint 2}} = 88.95 \cdot 0.03 = 2.67\,\text{N}\cdot\text{m}, \quad \tau_{\text{thumb, joint 3}} = 88.95 \cdot 0.015 = 1.33\,\text{N}\cdot\text{m}$

B. Index:

$\tau_{\text{index, joint 1}} = 106.74 \cdot 0.03 = 3.20\,\text{N}\cdot\text{m}, \quad \tau_{\text{index, joint 2}} = 106.74 \cdot 0.02 = 2.13\,\text{N}\cdot\text{m}, \quad \tau_{\text{index, joint 3}} = 106.74 \cdot 0.01 = 1.07\,\text{N}\cdot\text{m}$

C. Middle:

$\tau_{\text{middle, joint 1}} = 53.37 \cdot 0.03 = 1.60\,\text{N}\cdot\text{m}, \quad \tau_{\text{middle, joint 2}} = 53.37 \cdot 0.02 = 1.07\,\text{N}\cdot\text{m}, \quad \tau_{\text{middle, joint 3}} = 53.37 \cdot 0.01 = 0.53\,\text{N}\cdot\text{m}$

D. Ring:

$\tau_{\text{ring, joint 1}} = 53.37 \cdot 0.03 = 1.60\,\text{N}\cdot\text{m}, \quad \tau_{\text{ring, joint 2}} = 53.37 \cdot 0.02 = 1.07\,\text{N}\cdot\text{m}, \quad \tau_{\text{ring, joint 3}} = 53.37 \cdot 0.01 = 0.53\,\text{N}\cdot\text{m}$

E. Pinky:

$\tau_{\text{pinky, joint 1}} = 35.58 \cdot 0.03 = 1.07\,\text{N}\cdot\text{m}, \quad \tau_{\text{pinky, joint 2}} = 35.58 \cdot 0.02 = 0.71\,\text{N}\cdot\text{m}, \quad \tau_{\text{pinky, joint 3}} = 35.58 \cdot 0.01 = 0.36\,\text{N}\cdot\text{m}$

Tendon Analysis/Material Choice

- The thumb is under the most load
  - Joint 1 is max load for tendon
  - Assuming r is distance from thumb joint to end of tendon.

$$T_{\text{thumb, tendon}} = \frac{\tau_{\text{thumb, joint 1}}}{r_{\text{thumb, tendon}}} = \frac{4.45}{0.04} = 111.25\,\text{N}$$

- Area/diameter needed for each material
  - Tensile strength of kevlar (2600 MPa)
  - Tensile strength steel cable (1500 MPa)

$$A = \frac{F}{\sigma_{\text{max}}}$$

$$A = \frac{111.25}{2600 \times 10^6} \approx 4.28 \times 10^{-5}\,\text{m}^2 = 42.8\,\text{mm}^2 \quad A = \frac{111.25}{1500 \times 10^6} \approx 7.42 \times 10^{-5}\,\text{m}^2 = 74.2\,\text{mm}^2$$

$$r = \sqrt{\frac{4.28 \times 10^{-5}}{\pi}} = \sqrt{1.36 \times 10^{-5}} \approx 3.69 \times 10^{-3}\,\text{m} = 3.69\,\text{mm} \quad r = \sqrt{\frac{7.42 \times 10^{-5}}{\pi}} = \sqrt{2.36 \times 10^{-5}} \approx 4.86 \times 10^{-3}\,\text{m} = 4.86\,\text{mm}$$

Shear Stresses on Joints

- 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
- Cross sectional area of cylinders
- Final expanded shear stress equation in terms of torque, radius of moment arm, force at fingertip, and diameter of joint

$$V = F_t + F_g$$

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

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

$$A = \frac{\pi d^2}{4}$$

$$\tau = \frac{4\left(\frac{T}{r} + F_g\right)}{\pi d^2}$$

Shear Stresses on Joints cont.

- F_g from forces in finger distribution
- Assuming 1 cm moment arm
- Calculations for 2mm joint

$$\tau = \frac{4\left(\frac{T}{r} + F_g\right)}{\pi d^2}$$

- Max shear is apx 170 MPA
  - Most steel alloys have max shear of >240 Mpa
  - Other common options include Brass, Nickel, or Aluminum alloys

Joint	# Torque (T) (Nm)	# Shear Force V (N)	# Shear Stress τ (MPa)
Thumb 1	4.45	533.95	169.96
Thumb 2	2.67	355.95	113.30
Thumb 3	1.33	221.95	70.65
Index 1	3.2	426.74	135.84
Index 2	2.13	319.74	101.78
Index 3	1.07	213.74	68.04
Middle 1	1.6	213.37	67.92
Middle 2	1.07	160.37	51.05
Middle 3	0.53	106.37	33.86
Ring 1	1.6	213.37	67.92
Ring 2	1.07	160.37	51.05
Ring 3	0.53	106.37	33.86
Pinky 1	1.07	142.58	45.38
Pinky 2	0.71	106.58	33.93
Pinky 3	0.36	71.58	22.78

Mathematical Modeling: Forward Kinematics

- Determining position and orientation of the fingertip.
- Considered a simplified robotic finger
- Using Denavit-Hartenberg parameters
  - Provides a standardized method to assign coordinate frames and parameters to each link and joint

Typical dimensions for hand:

$$L_1 = 5\ cm$$

$$L_2 = 3\ cm$$

$$\theta_1 = 45° \ or \ \frac{\pi}{4}$$

$$\theta_2 = 30° \ or \ \frac{\pi}{6}$$

Link	Link Length	Link Twist	Offset	Joint Angle
1	L_1	0	0	θ_1
2	L_2	0	0	θ_2

Mathematical Modeling: Forward Kinematics Cont.

From Base to Link 1:

$$T_1 = \begin{bmatrix} \cos\theta_1 & -\sin\theta_1 & 0 & L_1\cos\theta_1 \\ \sin\theta_1 & \cos\theta_1 & 0 & L_1\sin\theta_1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

From Link 1 to Link 2:

$$T_2 = \begin{bmatrix} \cos\theta_2 & -\sin\theta_2 & 0 & L_2\cos\theta_2 \\ \sin\theta_2 & \cos\theta_2 & 0 & L_2\sin\theta_2 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$T = \begin{bmatrix} \cos\theta_1 & -\sin\theta_1 & 0 & L_1\cos\theta_1 \\ \sin\theta_1 & \cos\theta_1 & 0 & L_1\sin\theta_1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos\theta_2 & -\sin\theta_2 & 0 & L_2\cos\theta_2 \\ \sin\theta_2 & \cos\theta_2 & 0 & L_2\sin\theta_2 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} \cos(\theta_1+\theta_2) & -\sin(\theta_1+\theta_2) & 0 & L_1\cos\theta_1 + L_2\cos(\theta_1+\theta_2) \\ \sin(\theta_1+\theta_2) & \cos(\theta_1+\theta_2) & 0 & L_1\sin\theta_1 + L_2\sin(\theta_1+\theta_2) \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Mathematical Modeling: Forward Kinematics Cont.

Using the matrix multiplication:

$$x = L_1 \cos\theta_1 + L_2 \cos(\theta_1 + \theta_2)$$
$$y = L_1 \sin\theta_1 + L_2 \sin(\theta_1 + \theta_2)$$

Solving equations using typical dimensions:

$$y = 5\sin\left(\frac{\pi}{4}\right) + 3\sin\left(\frac{\pi}{4} + \frac{\pi}{6}\right)$$
$$= 5\left(\frac{\sqrt{2}}{2}\right) + 3\left(\frac{1}{2}\right)$$
$$\approx 3.54 + 1.50$$
$$\approx 5.04\,\text{cm}$$

$$x = 5\cos\left(\frac{\pi}{4}\right) + 3\cos\left(\frac{\pi}{4} + \frac{\pi}{6}\right)$$
$$= 5\left(\frac{\sqrt{2}}{2}\right) + 3\left(\frac{\sqrt{3}}{2}\right)$$
$$\approx 3.54 + 2.60$$
$$\approx 6.14\,\text{cm}$$

Conclusion:

- 6.14 cm in the x axis and 5.04 cm in the y axis from the base joint
- one can precisely determine the location of the finger in space
- Used for grasping objects or fine manipulations

Mathematical Modeling: Inverse Kinematics

- Determine angle to acquire precise positions

$$\theta_2 = \cos^{-1}\left(\frac{x^2 + y^2 - L_1^2 - L_2^2}{2L_1L_2}\right)$$

$$\theta_1 = \tan^{-1}\left(\frac{y}{x}\right) - \tan^{-1}\left(\frac{L_2 \sin\theta_2}{L_1 + L_2\cos\theta_2}\right)$$

Ex. If you wanted the end position to be (2,1)

Assume arm lengths are both L1=2, L2=1.5

The **maximum reach** of the arm is:

$$L_1 + L_2 = 2 + 1.5 = 3.5$$

The **distance to the target** is:

$$d = \sqrt{x^2 + y^2} = \sqrt{2^2 + 1^2} = \sqrt{5} \approx 2.236$$

Since $d \leq 3.5$, the target is **reachable**.

Mathematical Modeling: Inverse Kinematics

$$\cos(\theta_2) = \frac{2^2 + 1^2 - 2^2 - 1.5^2}{2(2)(1.5)}$$

$$= \frac{4 + 1 - 4 - 2.25}{6}$$

$$= \frac{-1.25}{6} = -0.2083$$

$$\theta_2 = \arccos(-0.2083)$$

$$\theta_2 \approx 102.02^\circ$$

$$\theta_1 = \arctan 2(y, x) - \arctan 2(L_2 \sin(\theta_2), L_1 + L_2 \cos(\theta_2))$$

$$\theta_1 = \arctan 2(1, 2) - \arctan 2\left((1.5 \cdot \sin(102.02^\circ)), (2 + 1.5 \cdot \cos(102.02^\circ))\right)$$

$$\theta_1 = \arctan 2(1, 2) - \arctan 2\left((1.5 \cdot 0.978), (2 + 1.5 \cdot (-0.208))\right)$$

$$\theta_1 = \arctan 2(1, 2) - \arctan 2(1.467, 1.688)$$

$$\theta_1 = 26.565^\circ - 40.998^\circ$$

$$\theta_1 = -14.44^\circ$$

Angles 1 and 2 are found which gives the end of the robotic arm a position of (2,1) with specific arm length values

Budget

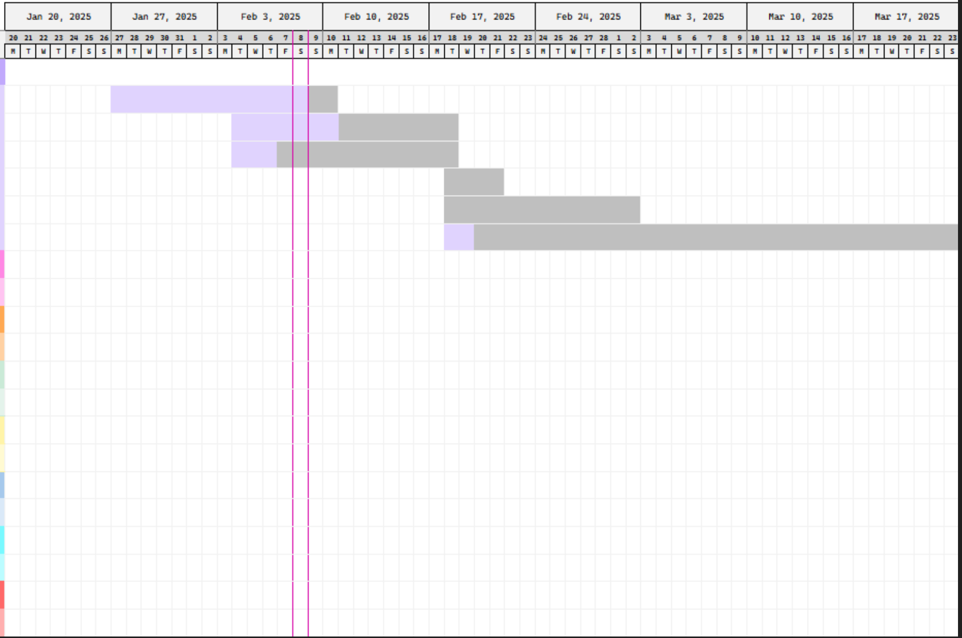
Item #	Item	Description	Planed Aquisiton Date	Actual Aquisiton Date	Price Per Unit	# of Units	Estimated Total Price	Actual Total Price
Budget Robotic Hand								
	Total Budget							$2,000
1	Motors	iPower GM2804 Gimbal Motor w/ AS5048A Encoder	3/10/2025		$38.90	10	$389.00	
2	Nylon 6	acts as the tendons for the hand (1/16' nylon chord)	3/10/2025		$15	1	$15.00	
3	Filament	Pro Series Carbon Fiber Nylon	3/10/2025		$62	2	$124	
5							$0	
6							$0	
7							$0	
8							$0	
9							$0	
10							$0	
	Estimated Remaining Budget							$1,472.00
	Actual Remaining budget							$2,000

Schedule

Humanoid Hand Gantt Chart

Project star Mon, 1/13/2025
Display week 2

TASK	ASSIGNED TO	PROGRESS	START	END	EST. HOURS	ACTUAL HOURS
Phase 1 (1st Prototype Demo)						
Work on Presentation 1	Team	90%	1/27/25	2/10/25	~	~
Establish Finger Design	Team	50%	2/4/25	2/18/25	~	~
Establish Control Scheme	Joseph, Noah	25%	2/4/25	2/18/25	10	
Order Preliminary Parts	Justin	0%	2/18/25	2/21/25		
Presentation 2	Team	0%	2/18/25	3/2/25	~	~
Prototype 1	Team	5%	2/18/25	3/31/25	~	~
Conclusion						



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[2] “Shadow Robot Company.” https://www.shadowrobot.com/

[3] “DexHand - An Open Source Dexterous Humanoid Robot Hand,” *DexHand - An Open Source Dexterous Humanoid Robot Hand*. https://www.dexhand.org/

[4] “Free CAD Designs, Files & 3D Models | The GrabCAD Community Library,” *Grabcad.com*, 2025. https://grabcad.com/library/sup-open-arms-1 (accessed Jan. 25, 2025).

[5] M. Controzzi, C. Cipriani, B. Jehenne, M. Donati and M. C. Carrozza, "Bio-inspired mechanical design of a tendon-driven dexterous prosthetic hand," 2010 Annual International Conference of the IEEE Engineering in Medicine and Biology, Buenos Aires, Argentina, 2010, pp. 499-502, doi: 10.1109/IEMBS.2010.5627148. keywords: {Joints;Fingers;Thumb;Humans;Actuators;Flexible printed circuits;Wrist}

[6] G. Gao, L. Gerez, and Minas Liarokapis, “Adaptive, Tendon-Driven, Affordable Prostheses for Partial Hand Amputations: On Body-Powered and Motor Driven Implementations,” *PubMed*, pp. 6656–6660, Jul. 2019, doi: https://doi.org/10.1109/embc.2019.8857187.

Sources

[7]“Advanced Humanoid Robotic Hand Technologies | T2 Portal.” *Technology.nasa.gov*, technology.nasa.gov/patent/MSC-TOPS-102.

[8]Borghesan, G, et al. *Design of Tendon-Driven Robotic Fingers: Modeling and Control Issues*.

[9]Kim, Uikyum, et al. “Integrated Linkage-Driven Dexterous Anthropomorphic Robotic Hand.” *Nature Communications*, vol. 12, no. 1, Dec. 2021, https://doi.org/10.1038/s41467-021-27261-0.

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