# Robotic Arm

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# Project Description

**Project Description**

- Stroke is the leading cause of upper limb disability.
- Survivors often lose mobility in one arm, limiting daily activities.
- Goal: develop a **waist-mounted robotic arm** that
  - Offers **active gravity compensation**
  - Remains **lightweight, low-profile, and energy efficient**
  - Enables the arm to rest naturally by the user's side.
- **Client:** Dr. Zach Lerner, Associate Professor of Mechanical Engineering, NAU.
- **Sponsorship:** W.L Gore

# Design Requirements

## Customer Requirements

- Comfortability
- Range of Motion
- Safety
- Cost for Consumer
- Durability
- Ease of Use
- Low-Profile

## Engineering Requirements

- Degrees of Freedom (3)
- Quality of Components (<$1400)
- Quality of Materials (<$1000)
- Manufacturing Costs (<$1000)
- Torque Speed (70 deg/s)
- Battery Life (approx. 8 hours)
- Weight (< 2 kgs)

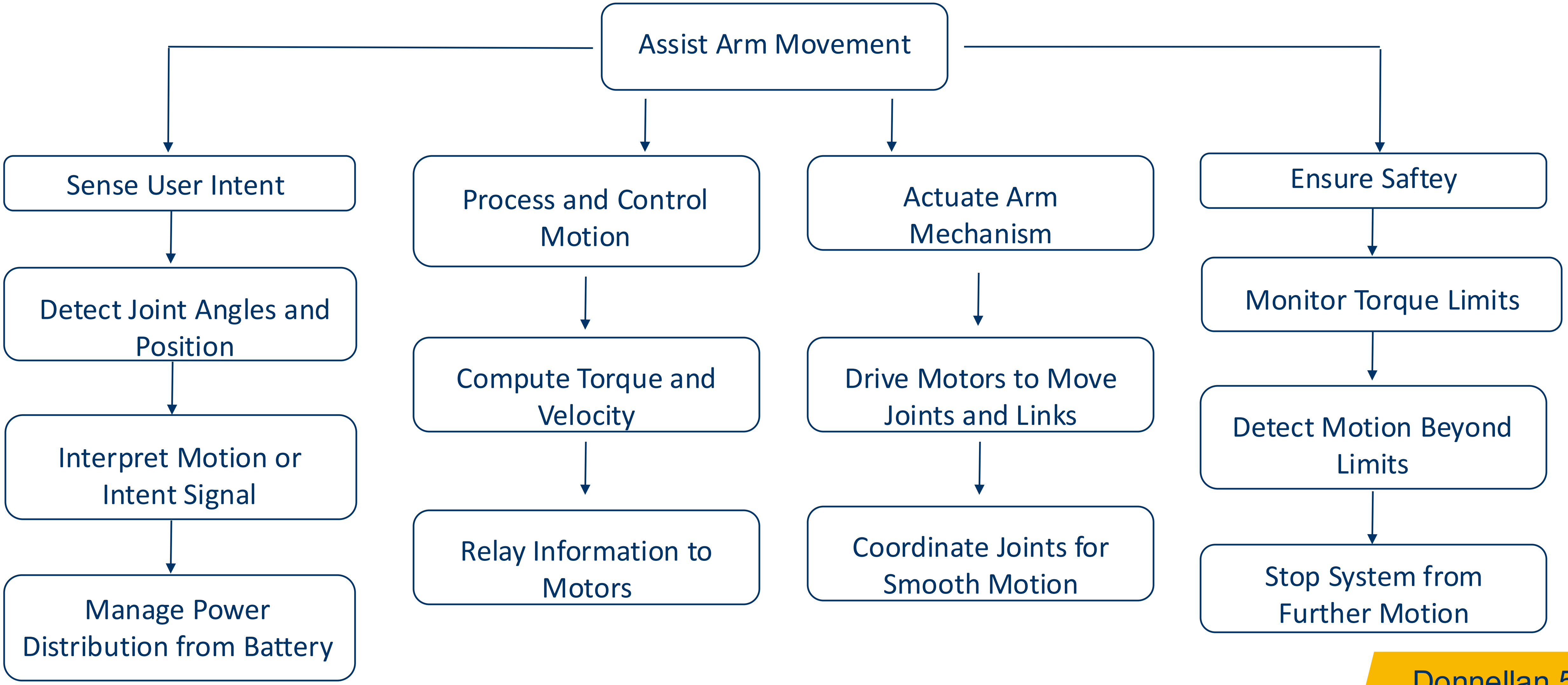
# Design Requirements QFD

| | Degrees of Freedom | Quality of Components | Quality of Materials | Manufacturing Cost | Torque Speed | Battery Life | Weight |
|---|---|---|---|---|---|---|---|
| Degrees of Freedom | | | | | | | |
| Quality of Components | pos | | | | | | |
| Quality of Materials | | neg | | | | | |
| Manufacturing Cost | pos | | pos | | | | |
| Torque Speed | | pos | | | | | |
| Battery Life | neg | pos | | neg | pos | | |
| Weight | pos | pos | pos | pos | pos | pos | |

| Correlation | |
|---|---|
| Positive | pos |
| Negative | neg |

| | | | Engineering Requirements | | | | | | | Benchmarking | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Relative Weight (%) | Customer Weights | Customer Requirments | Degrees of Freedom | Quality of Components | Quality of Materials | Manufacturing Cost | Torque Speed | Battery Life | Weight | Poor | Adequate | Excellent |
| 11 | 4 | Comfortable | 3 | 3 | 3 | 1 | 3 | 3 | 9 | | C | AB |
| 22 | 5 | Range of Motion | 9 | 3 | 3 | 1 | 1 | 1 | 1 | A | B | C |
| 10 | 5 | Safety | 3 | 9 | 9 | 1 | 9 | 1 | 3 | | | ABC |
| 10 | 2 | Cost for Consumer | 3 | 9 | 9 | 9 | 3 | 3 | 3 | AC | B | |
| 5 | 3 | Durabiltiy | 1 | 9 | 9 | 1 | 1 | 1 | 9 | | B | AC |
| 5 | 4 | Ease-of-use | 9 | 3 | 3 | 1 | 9 | 3 | 3 | BC | A | |
| 22 | 3 | Low-Profile | 3 | 1 | 3 | 3 | 3 | 9 | 9 | ABC | | |
| Technical Requirement Units | | | N/A | $ | $ | $ | °/s | Hours | kgs | | | |
| Technical Requirement Targets | | | 4 | <1400 | <1000 | <1000 | 60 | >8 | <2 | | | |

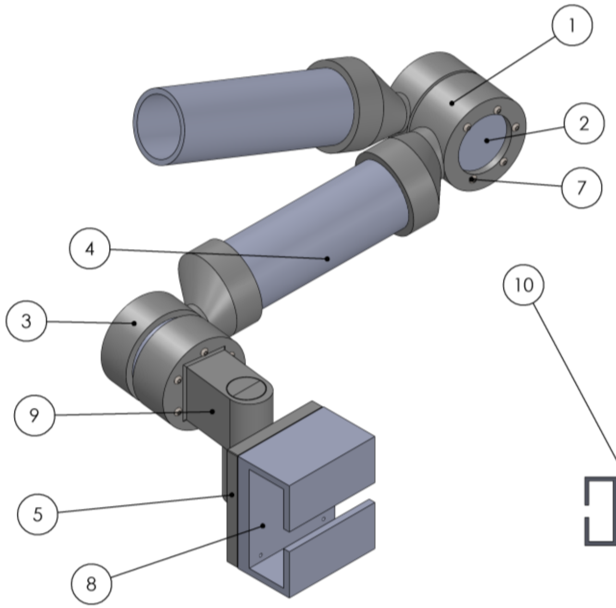
# Functional Decomposition



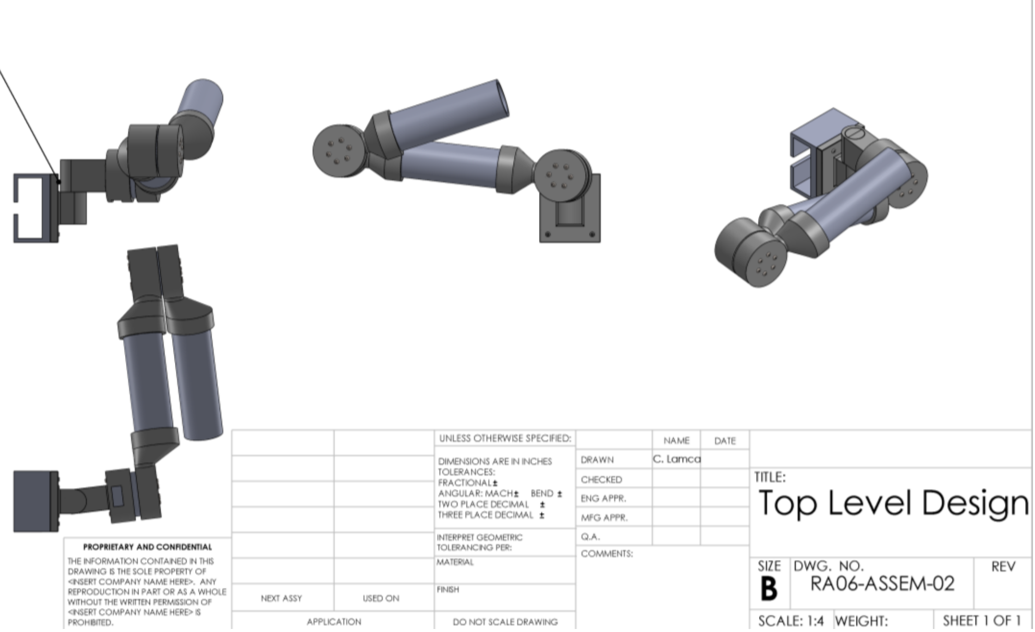
# Top Level Design Model

Top Level Design Function:

- Hinge subassembly at the hip to manually control DoF
- 1st motor & joint subassembly
  - Motor mount stabilizes motor during actuation. This actuation articulates the first link
- 2nd motor & joint subassembly
  - This second motor and link extends the reach of the arm and determines the final position of the arm.
- Ultimate control of the end effector




| ITEM NO. | PART NUMBER | DESCRIPTION | QTY. |
|---|---|---|---|
| 1 | RA06-DET009 (Motor Mount) | | 1 |
| 2 | RA06-DET005-ASSEM (AK45-36) | | 2 |
| 3 | RA06-DET009-02 | | 2 |
| 4 | PVC Pipe | | 2 |
| 5 | RA06-DET010-02 (Hinge Bottom) | | 1 |
| 6 | RA06-DET001 (Waist Belt) | Waist Belt | 1 |
| 7 | 91239A113 | Button Head Hex Drive Screw | 22 |
| 8 | RA06-DET002 (Arm Support Clip) | Support for Arm to User | 1 |
| 9 | RA06-DET011-03 | | 1 |
| 10 | 91239A811 | Button Head Hex Drive Screw | 4 |



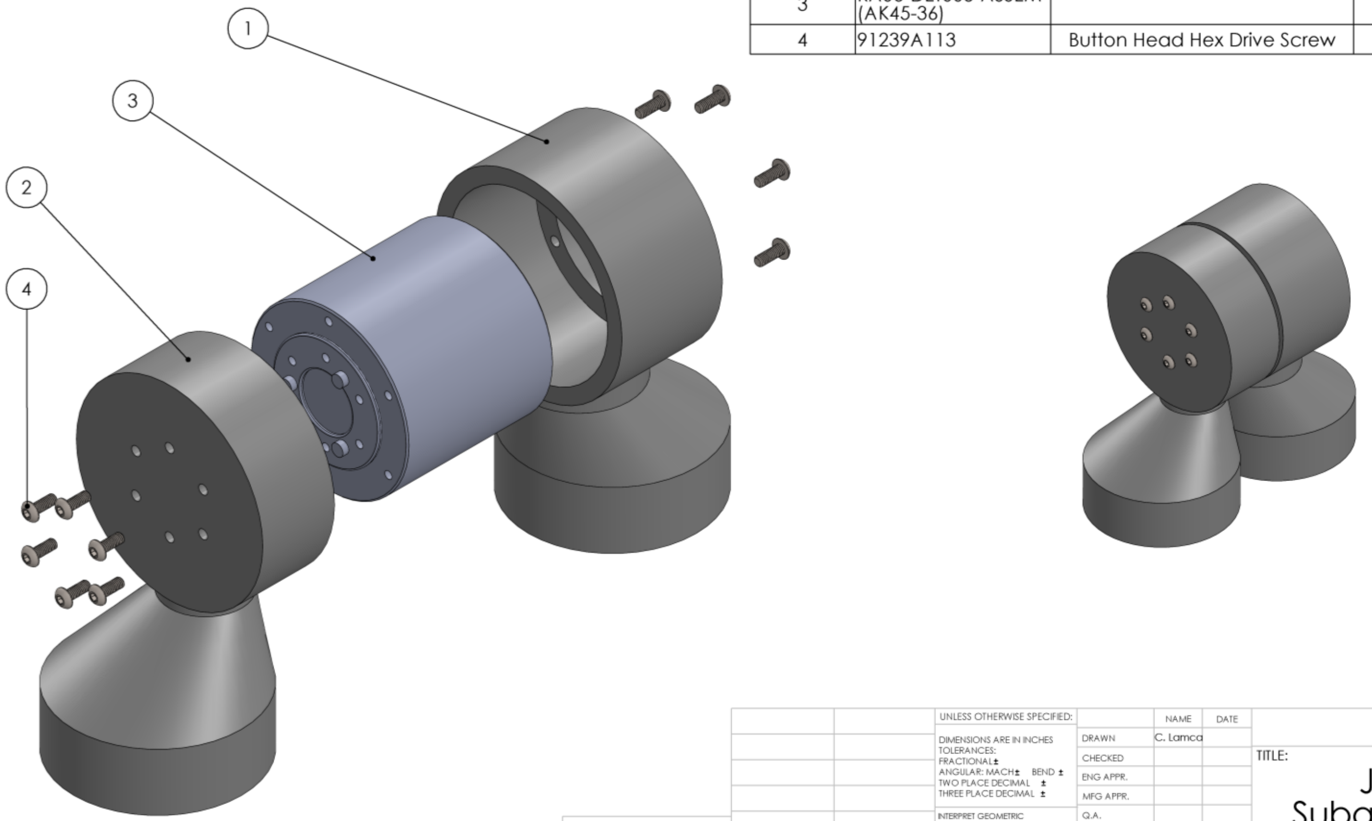

*Refer to page 1 for functions and page 2 for enlarged model

# Subassembly Model 1 – Joint

## Joint Subassembly Function:

- Motor mount (right) holds motor with 5 screws to stabilize
- The motors extruded pins locate into holes on the inner wall of the next mount (left) and secured by 6 screws
- As the motor operates, the right-side mount stays static and the left mount articulates the link (not pictured)

| ITEM NO. | PART NUMBER | DESCRIPTION | QTY. |
|---|---|---|---|
| 1 | RA06-DET009 (Motor Mount) | | 1 |
| 2 | RA06-DET009-02 | | 1 |
| 3 | RA06-DET005-ASSEM (AK45-36) | | 1 |
| 4 | 91239A113 | Button Head Hex Drive Screw | 11 |

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NEXT ASSY | USED ON
APPLICATION

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING

| | NAME | DATE |
|---|---|---|
| DRAWN | C. Lamca | |
| CHECKED | | |
| ENG APPR. | | |
| MFG APPR. | | |
| Q.A. | | |

COMMENTS:

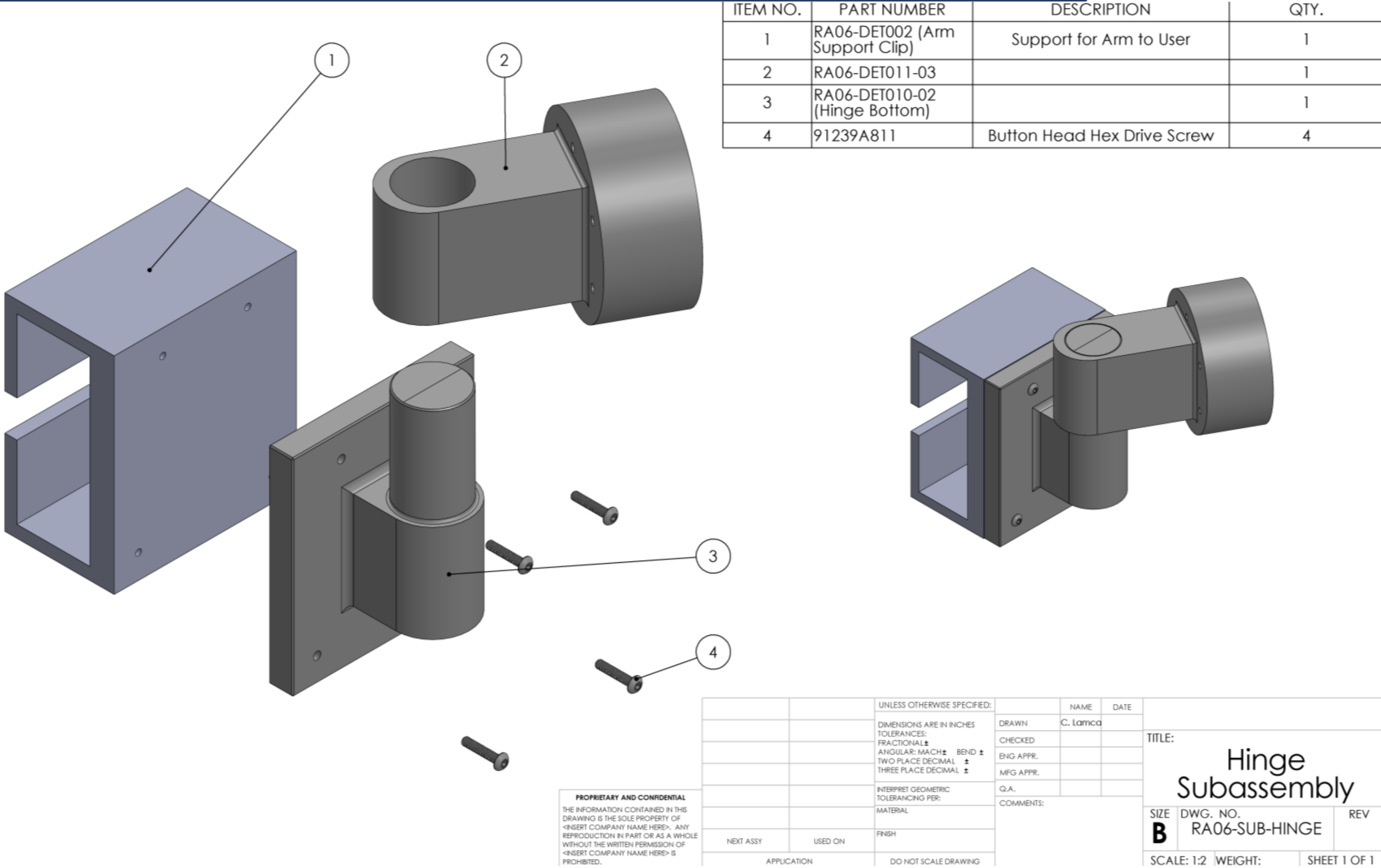
TITLE: Joint Subassembly
SIZE B | DWG. NO. RA06-SUB-JOINT | REV
SCALE: 1:4 | WEIGHT: | SHEET 1 OF 1

*Refer to page 1 for functions and page 3 for enlarged model

# Subassembly 2 Model - Hinge

Hinge Subassembly Function:

- Hinge subassembly is fixed to the waist belt (not pictured) via the belt clip
- 1st motor mount slides onto the hinge shaft
- At the use moves their arms orientation from in front to the side, the hinge will pivot around the shaft, controlling this DoF




*Refer to page 1 for functions and page 4 for enlarged model

# Battery Run Time Calculation

What is the time that the two battery can last for the motors while being used?

Battery Given was HRB 1800mAh 6S 22.2V 50C LiPo Battery by our client.

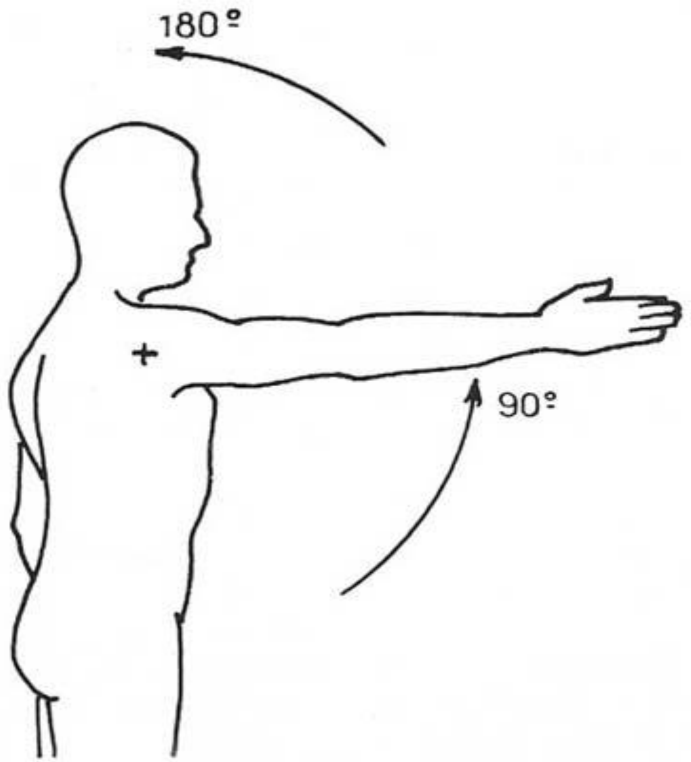
The motor we our using is the AK 45-36 motor which has a rated voltage and current were found from

$$Run\ Time = \frac{Battery\ Voltage \cdot Battery\ Capacity}{Number\ of\ motors \cdot (Rated\ Voltage \cdot Rated\ Current)}$$

$$Run\ Time = \frac{22.2\ V\ \cdot 3.6\ Ah}{2 \cdot (24\ V \cdot 2\ A)} \approx 49\ minutes$$

# Engineering Calculations

- Arm (shoulder flexion) velocity
- Shoulder flexion from hanging straight down (0 degrees) to straight forward (90 degrees)
- Average shoulder to elbow length: 330mm (13in)
- Average angular velocity: $w_{avg} = \frac{\Delta\, \theta}{Time\ t}$
- Using $\Delta\, \theta$ = 90 degrees and time 1.28 seconds.
- $w_{avg} = \frac{\Delta\, \theta}{Time\ t} = 1.227 \frac{rad}{s}$
- Linear velocity (elbow): $v = \ w_{avg} * r = 0.405 \frac{m}{s}$



# Engineering Calculations – Arm Position (inverse Kinematics)

$$x \geq 0, y \geq 0, z \geq 0$$

$$x^2 + y^2 + z^2 \leq R^2$$

$$R_z(\varphi) = \begin{matrix} \cos(\varphi) & -\sin(\varphi) & 0 & 0 \\ \sin(\varphi) & \cos(\varphi) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{matrix}$$

$$R_y(+)(\theta_1) = \begin{matrix} \cos(\theta) & 0 & -\sin(\theta) & 0 \\ 0 & 1 & 0 & 0 \\ \sin(\theta) & 0 & \cos(\theta) & 0 \\ 0 & 0 & 0 & 1 \end{matrix}$$

$$T_x(L) = \begin{matrix} 1 & 0 & 0 & L \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{matrix}$$

$$FK = T_0{}^2 = R_z(\varphi) R_y(+)(\theta_1)\, T_x(L)\, R_y(+)(\theta_2)\, T_x(L)$$

$$x, y, z = (200,180,150)mm$$

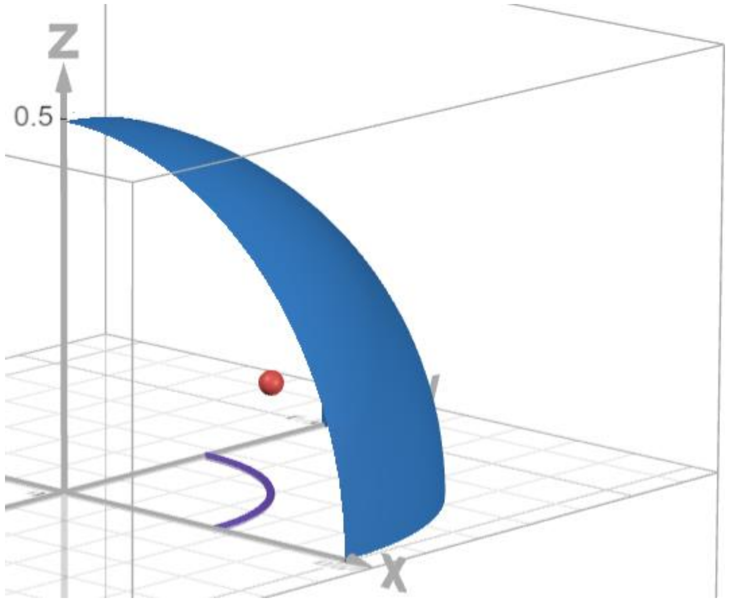
$$d = \sqrt{(200^2 + 180^2 + 150^2)} \approx 308mm \ \leq 496mm$$

$$\varphi = atan2(y, x) = atan2(180,200) \approx 41.99°$$

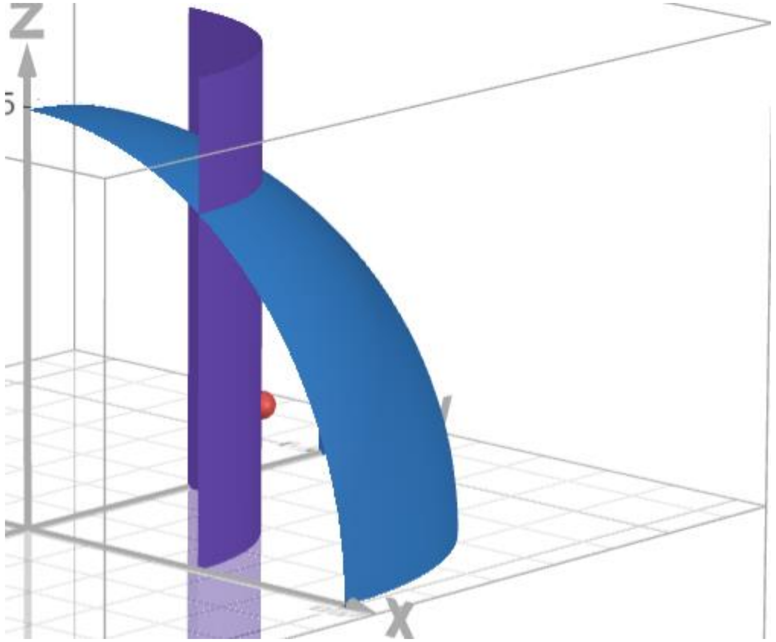
$$z\ rotation\ aligns\ target\ in\ 2D\ r - z\ plane$$

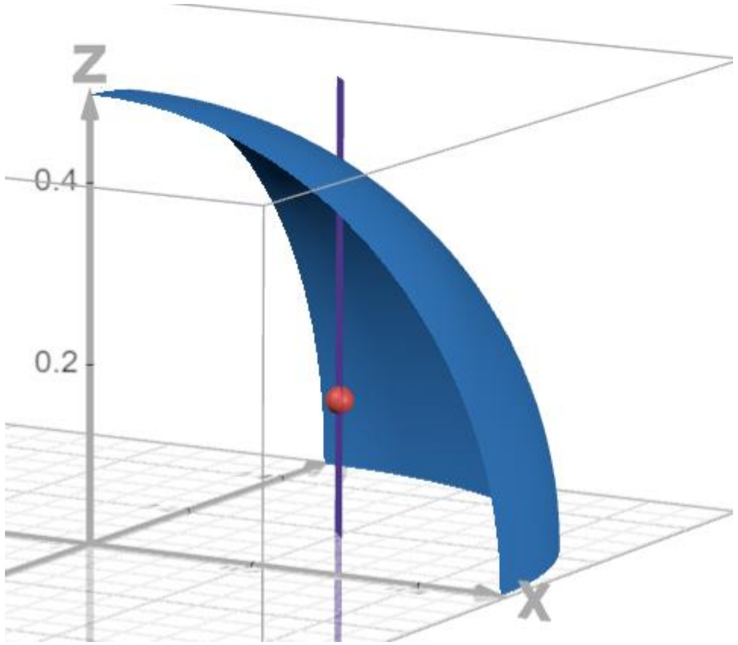
$$r = \sqrt{x^2 + y^2}$$

$$d = \sqrt{r^2 + z^2}$$



# Engineering Calcs (IK)




$$\cos(\theta_2) = \frac{d^2 - L^2 - L^2}{2L^2}$$

$$\alpha = atan2(z, r)$$

$$\beta = atan2(Lsin(\theta_2) + lcos(\theta_2))$$

$$\theta_1 = \alpha - \beta$$

$$\varphi = 41.99°$$

$$\theta_1 = -22.47°$$

$$\theta_2 = 103.21°$$

# Motor Mount Shear

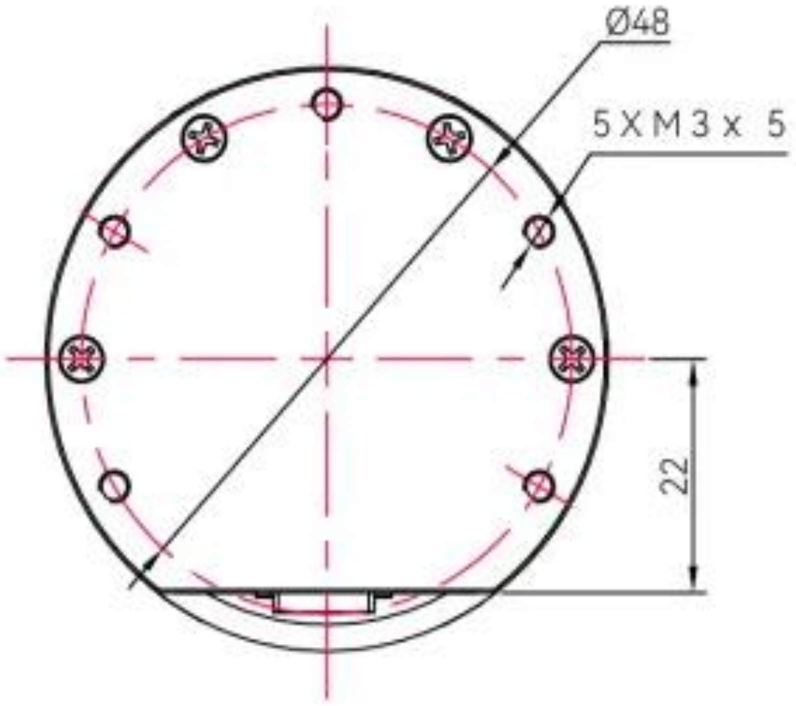
- What is the minimum thickness for the motor mount to withstand maximum shear?

$$\tau = \frac{F_{bolt}}{t * h}$$

$$F_{bolt} = \frac{T_{design}}{r * n}$$ , where n = number of bolts

$$T_{design} = 24\ N * m$$

$$\tau = \frac{40\ N}{t} < 11.4\ MPa$$




- t must be larger than 3.5 mm to withstand maximum shear stress.

# FEA – Hinge Shaft

- Bending on the hinge shaft due to the torque of the arm
- Calculated the sum of moments from each component at maximum extension from the body
- Modeled custom PLA material in SolidWorks to achieve a realistic analysis
- FoS was found to be around 50.

FEA for Hinge Shaft

| Mass ($g$) | Distance from Hinge Shaft ($mm$) | Detail | Moment ($g * mm$) |
|---|---|---|---|
| 115 | 250 | Motor Mount 1 | 28750 |
| 101 | 250 | Motor Mount 2 | 25250 |
| 6.05 | 250 | Bolts | 1512.5 |
| 340 | 250 | Motor 2 | 85000 |
| 115 | 120 | PVC 1 | 13800 |
| 115 | 300 | PVC 2 | 34500 |
| | | Total Moment ($g \cdot mm$) | 188813 |
| | | Total Moment ($N \cdot mm$) | 1851.6 |

$$M = F \cdot L$$

$$F = \frac{M}{L}$$, where M is the total moment and L is the diameter of the top of the shaft

$$F = \frac{1851.6\ (N \cdot mm)}{25\ (mm)} = 74.064\ N$$, used to create the couple moment on the top of the shaft

# FEA – Hinge Shaft Simulation Results

| Property | Value | Units |
|---|---|---|
| Elastic Modulus | 3500000000 | N/m^2 |
| Poisson's Ratio | 0.36 | N/A |
| Shear Modulus | 1300000000 | N/m^2 |
| Mass Density | 1240 | kg/m^3 |
| Tensile Strength | 60000000 | N/m^2 |
| Compressive Strength | 65000000 | N/m^2 |
| Yield Strength | 50000000 | N/m^2 |

[2] Material properties of PLA


<u>Simulation Results:</u>

Maximum Stress: **9.8*10^5 N/m^2**

Maximum Deformation: **0.019 mm**

Factor of Safety: **>50**

*Refer to page 3 & 5 for visualization of the hinge and its purpose in the design

# Bill of Materials

| Item | Price |
|---|---|
| 2 AK45-36 motor (purchased) | $371.80 |
| 3D filament (purchased) | $35.99 |
| Battery (purchased) | $67.12 |
| Waist belt (purchased) | $107.74 |
| Hinge | $15 |

# FMEA

| Part # and Functions | Potential Failure Mode | Potential Effect(s) of Failure | Potential Causes and Mechanisms of Failure | RPN | Recommended Action |
|---|---|---|---|---|---|
| Link 1, | 3d printed link breaks under stress of the motor torque and the weight of the arm | the 3d printed material could crack and splinter pieces but these would be low velocity. Arm could collapse therfore loss of support could injur clients arm. | failure in control of motor causing it to spin past the rotation we want.wall thickness of printed geometry could be too thin. | 140 | test different materials at different torque speeds and find what will not break. Also include FEA of material and geometry |
| Link 2 | fracture under impact | loss of elbow support / robitc arm/ ability. | thin wall, large impact, poor printing material. | 140 | thicken wall, try different material. |
| Motor 1 (base) | 1:heat overload/ stall | motor shutdown, motor may heat up could cause burining around 3d printed areas. Arm could freeze mid motion | torque demand too high, no proper cooling method. Software malfunction | 112 108 | improve ventilation, invest in a heat sink. |
| | 2: coil winding damage | electrical short causing potential fire and loss of drive | moisture in motor, poor insulation | | Add waterproof cover to prvent moisture getting in. |
| Motor 2 | thermal overload | motor shutdown, motor may heat up could cause burining around 3d printed areas. Arm could freeze mid motion | continuous load, user leaning heavily on elbow cup. | 112 | add torque limit and thermal cutoff. Improve ventilation. |

# FMEA

| | | | | | |
|---|---|---|---|---|---|
| waist belt | 1:buckle or strap tear or detachment<br>2: belt slippage during use | the robotic arm could drop and cause damage or injury to client<br>Poor control, cause unexpected motion which could damage equipment or harm client | fatigue or overload of belt or other mecanichal componetns<br>poor fabric friction, belt not in high enough tension / not secure around the waist | 120<br>144 | to use a industry standard belt, add secondary safety tether.<br>Additional tether added to reduced slip chance, extra friction pads |
| hinge | crack or deformation around bolt holes. | 0 | screws/bolts too lose or too tight weak hinge condition. Undersized pin, poor alignment | 105 | invest in a reliable hinge or prototype to find a better joint. |
| motor mount | crack or deformation around bolt holes. | motor misalignment, large vibration screw/nut slipping out. Could cause the arm to fall and smash sudden movemnet may hurt client. | over tightning of screws /bolts. Poor print orientation | 140 | re print piece checking print orientation. |
| battery pack | 1: battery pack overheating/ shorting<br>2:connector loosened | a short or overheating could cause a combustion causing a fire.<br>System reset could cause jarring/sporadic movement. Could potentially injure client | physical damage to the battery or a internal short.<br>Vibration in battery, poor internal wiring. | 120<br>100 | incase in fire retardant material.<br>Use locking or threading connectors to stop vibrations from loosening the wires.add capacitor bank to smooth voltage spikes. |

# Testing Procedures

Future Testing:

- Impact Test
  - Measure the arms ability to withstand an impact using a wall or other natural environment
- Weight
  - Measure the weight of the arm using a scale to maintain a reasonable weight
- Battery Endurance Test
  - Measure how long the battery can last with motors in use and not in use
- Mobility test
  - Device to see if all degrees of freedom are met
- Activity Test
  - Space to perform various everyday activities and evaluate the arms effectiveness

# Budget

- Funding from W.L Gore: $4000
- NAU 5% processing fee: -$200
- Fundraising (at least %10): $400
- Total Est. Budget: $4200

- We have an estimate of $3675 for total cost of possible items. The team will have a remaining balance of $525. We will need to fundraise more to begin prototyping.

| Expenses | | |
|---|---|---|
| Category | Items(s) | Cost |
| Tools and materials: | 3D printer Parts | $100 |
| | 3D printer Filament | $35.99 |
| Manufacturing: | | $300 |
| Parts: | Motors | $371.80 |
| | Battery | $67.12 |
| | Miscellaneous Parts | $700 |
| Prototyping: | 1st | $1200 |
| | 2nd | $900 |
| TOTAL: | | $3674.91 |

# Fundraising

- Need to accumulate 10% of the $4,000 budget for a minimum of $400 total
- In talks with multiple companies regarding sponsorships, services, or cash donations
- We plan to fundraise the entire 10% by the time of testing of prototype 1

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# Schedule

Plan duration    Actual Start    Completed    Beyond Completion

| | August | | | | September | | | | October | | | | November | | | | December | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | wk1 | wk2 | wk3 | wk4 | wk5 | wk6 | wk7 | wk8 | wk9 | wk10 | wk11 | wk12 | wk13 | wk14 | wk15 | wk16 | |
| Requirements/ research | | | | | | | | | | | | | | | | | | | | |
| Equations | | | | | | | | | | | | | | | | | | | | |
| Presentation 1 | | | | | | | | | | | | | | | | | | | | |
| Conceptual designs | | | | | | | | | | | | | | | | | | | | |
| Fundraising | | | | | | | | | | | | | | | | | | | | |
| Presentation 2 | | | | | | | | | | | | | | | | | | | | |
| Begin modelling | | | | | | | | | | | | | | | | | | | | |
| Testing prototype 1 | | | | | | | | | | | | | | | | | | | | |
| Presentation 3 | | | | | | | | | | | | | | | | | | | | |
| 1st Prototype Demo | | | | | | | | | | | | | | | | | | | | |
| Begin prototype 2 | | | | | | | | | | | | | | | | | | | | |
| Testing for Prototype 2 | | | | | | | | | | | | | | | | | | | | |
| 2nd Prototype Demo | | | | | | | | | | | | | | | | | | | | |

# Thank you
# And
# Any Questions?

# Appendix

[1] “AK45-36 Robotic Actuator – Ultra-High Torque, 36:1 Gear Ratio,” *CubeMars*, 2025. https://www.cubemars.com/product/AK45-36.html

Mechanical and Geometric Performance of PLA-Based Polymer Composites Processed by the Fused Filament Fabrication Additive Manufacturing Technique - PMC

[2] S. Farah, D. G. Anderson, and R. Langer, “Physical and mechanical properties of PLA, and their functions in widespread applications — A comprehensive review,” MIT, 2016. [Online]. Available: https://dspace.mit.edu/bitstream/handle/1721.1/112940/Anderson_Physical%20and%20mechanical%20properties.pdf?sequence=1