Brunel University London

ME5692 Group Project: Design and Development of a Brunel Hexapod Robot

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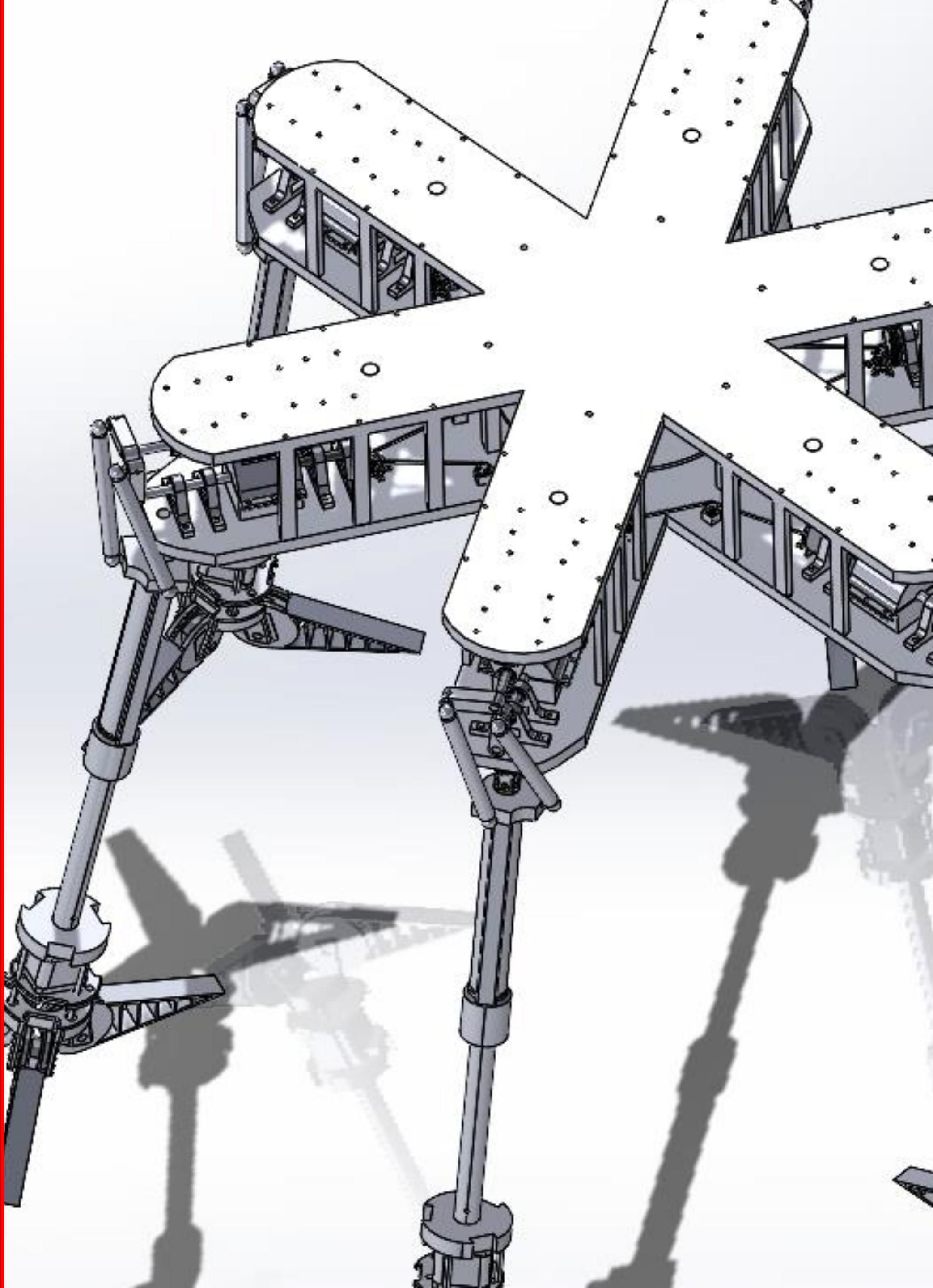
Hamza Al-Siyabi	**2429643**
Anbit Chhetri	**1914191**
Huimin Wang	**2407446**

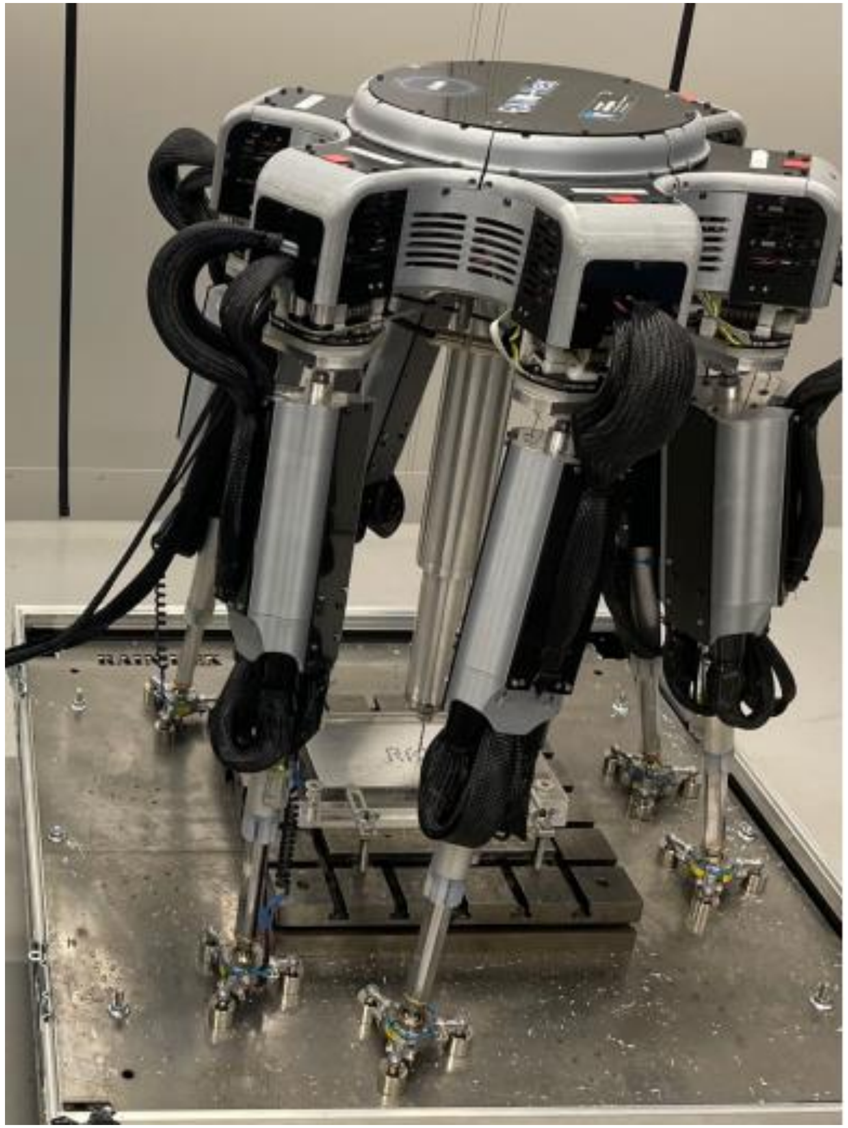


Scope of the Project + Background

What is the Importance of Hexapod?
- Exploration [In-situ repairs]
- Inspection of tight crawl locations
- Security
- Education environment

Hexapod vs tripedal vs quadrupedal
- Adaptability
- Gait Flexibility[Wave, Tripod, Ripple]
- Higher Fault tolerance

Key Concepts:
- Walking Locomotion
- Dual Purpose End Effector
- U-P-U Kinematic Chain

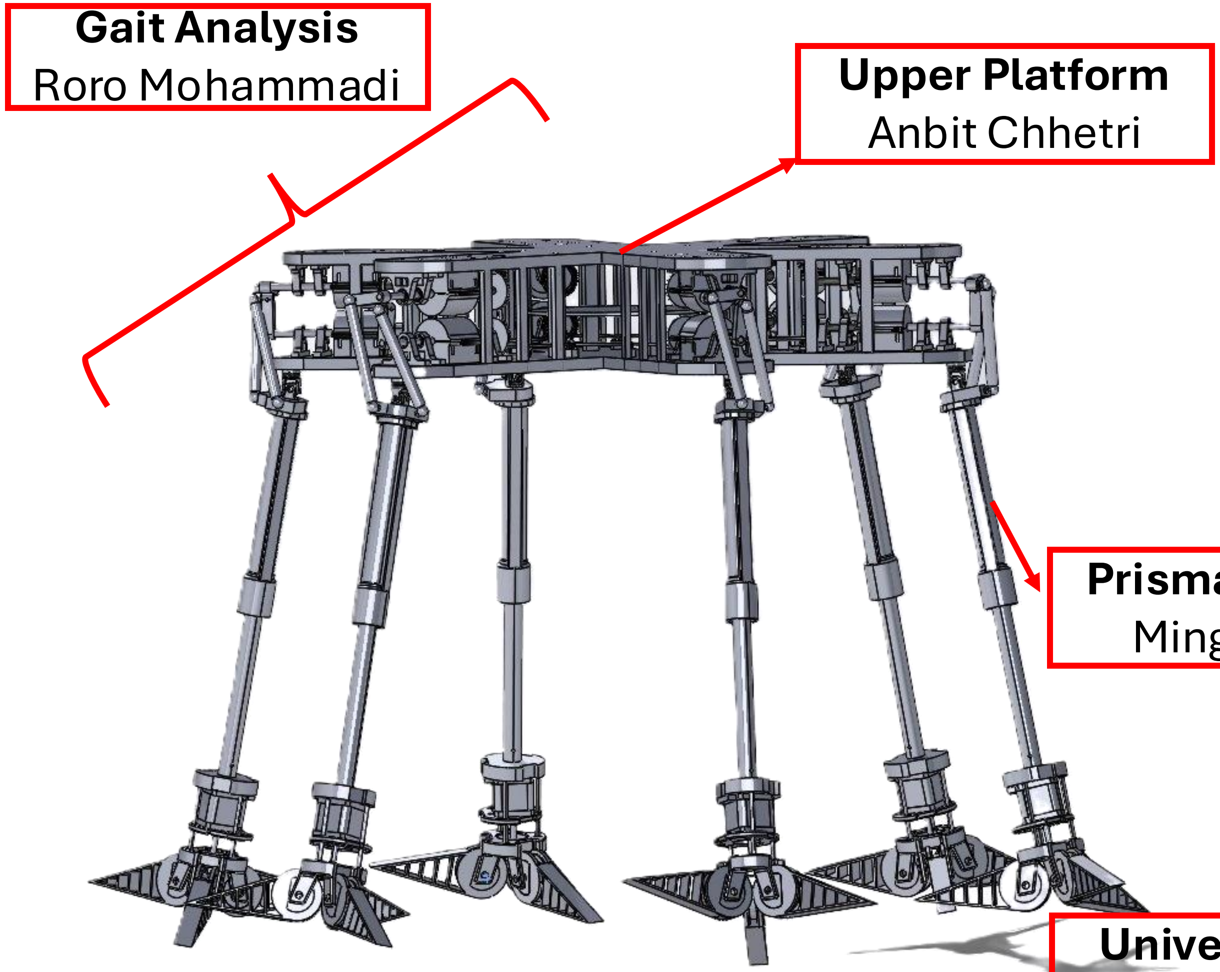


Brunel Hexapod Robot

End Goal:
- Design and Development of hexapod robot

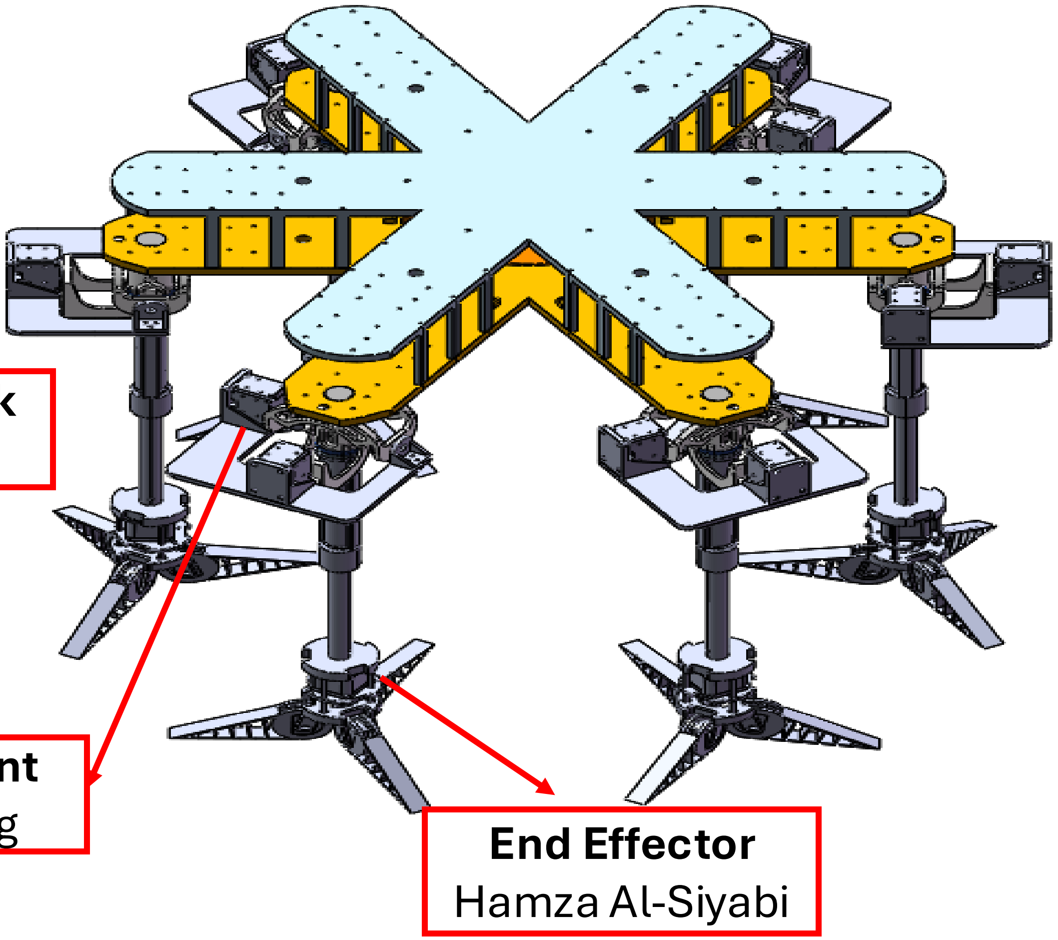
Tasks Required:
- FEA analysis
- CAD Design
- Matlab Simulation

Optimised Hexapod Robot Assembly



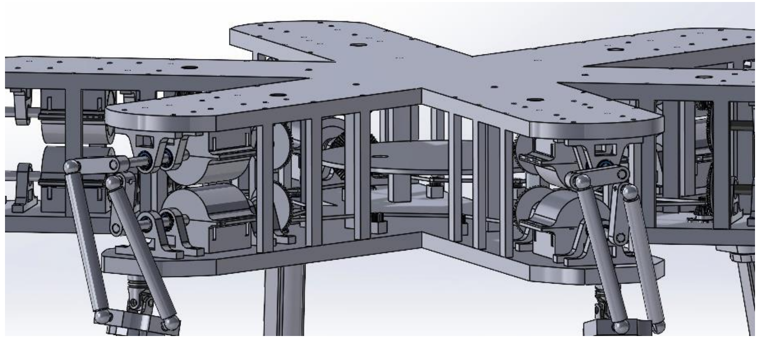
Assembly 1:
Electromagnetic Clutch Mechanism

Assembly 2 : Gimbal Mechanism



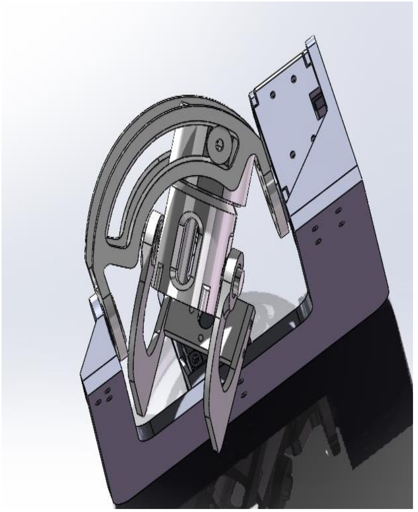
Individual Roles

Upper Platform Anbit Chhetri (1914191)



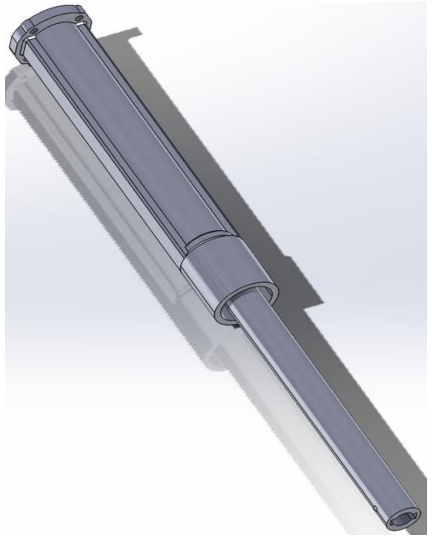
Upper Platform Structural Refinement
&
Intergration of electronic components

Universal Joint Huimin Wang (2407446)



Design of weak universal joints
&
Material Optimisation
&
FEA analysis
&
Motor Optimisation

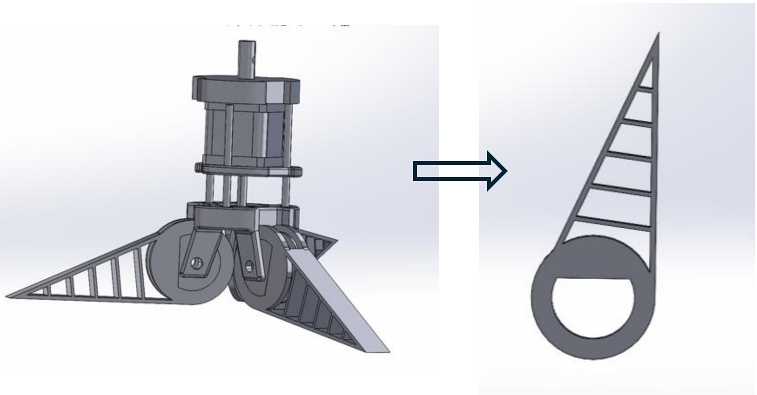
Prismatic Link Mingi Choi (2446225)



Material Optimisation
&
3D Printing Prototype Guideline

FEA + WDM

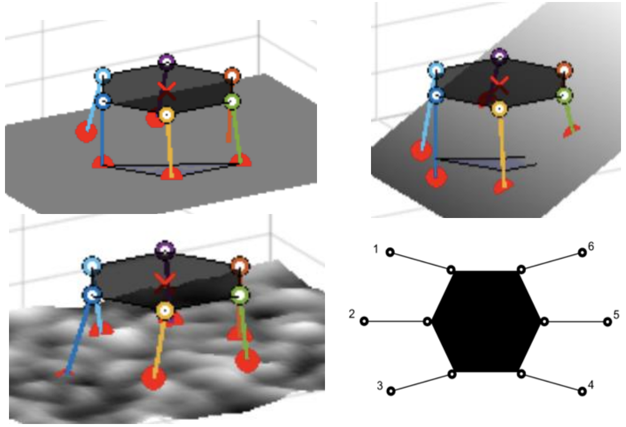
End Effector Hamza Al-Siyabi (2429643)



- Design and development of Fin Ray structured end effector
- CAD modelling of 12 design variations (rib angle & wall thickness)
- Investigate the impact of material stiffness (TPU A85 vs A95) on grip performance

Gait Analysis Roro Mohammadi (2107729)

- Gait Simulations and optimisations
- Terrain-Aware Design
- Design optimisations



Upper Platform

Anbit Chhetri (1914191)

Aim: Optimization and completion of the existing upper platform design

Objectives:

- Analysis of the existing design to understand flaws and improvement potential.
- Restructuring the design to improve on flaws and for the purpose of rapid prototyping.
- Minimizing the electrical requirement of the design and integration of electrical component in the upper platform

Problems

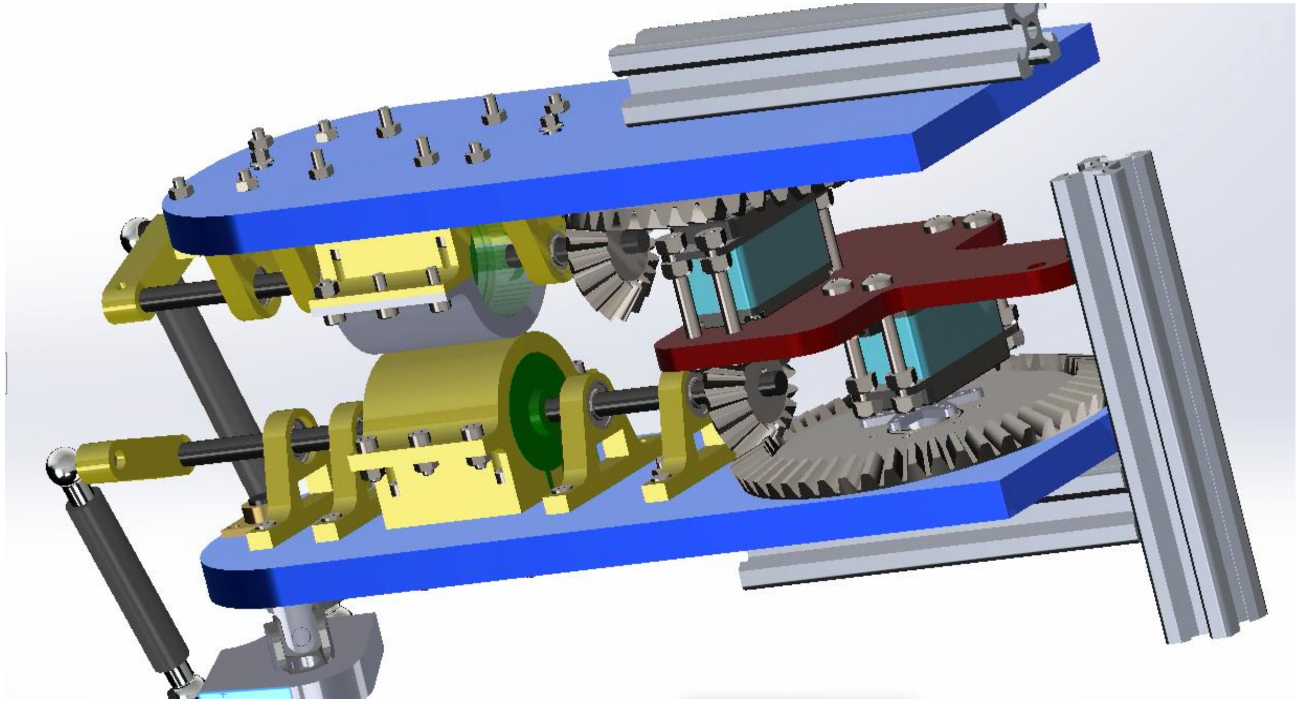
Existing flaws in Design:

- Partially developed design – 2 motor per leg
- Inaccurate Connections and measurements
- Overengineered
- Poor structural support.

Solutions

Combatting flaws:

- A full hexapod design version with dual motor mechanism
- New gear model with connection, accurate bolt placements
- Reduction of Weight.
- Extra wall support in certain section.

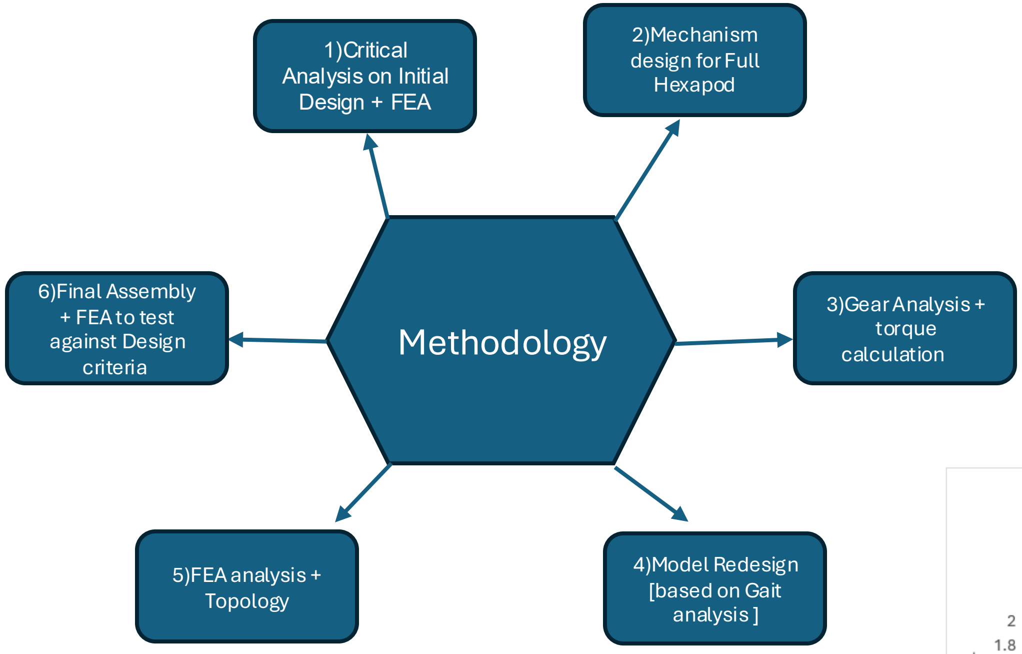


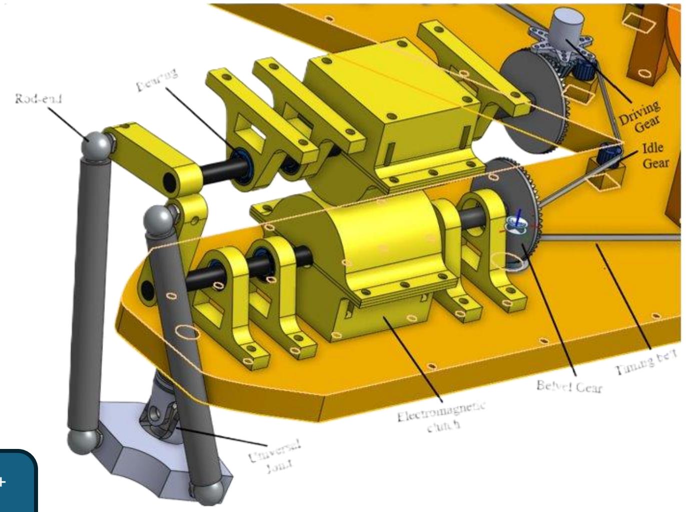
Original upper platform design

Upper Platform

Anbit Chhetri (1914191)

Methodology





$$\tau = m \cdot g \cdot r\,cos(\theta)$$

where m=mass of the leg; g= gravity; r= centre of mass;θ= lift angle.

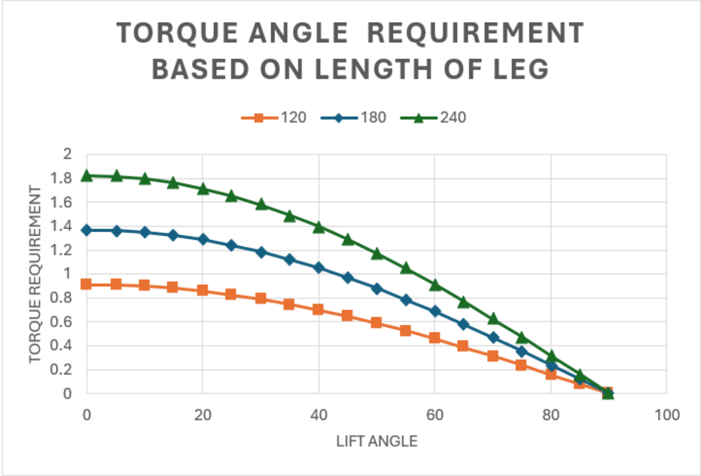


Figure A5: Comparison of Torque and lift angle

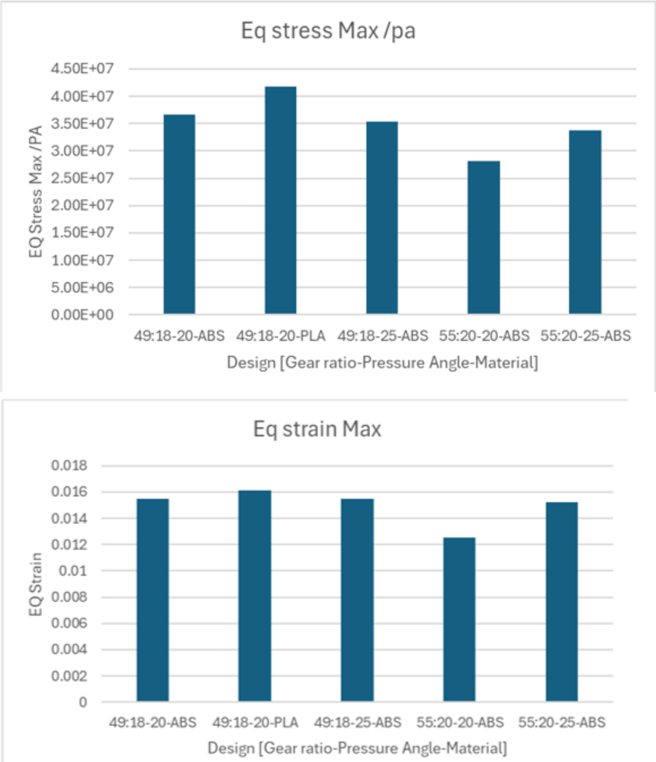
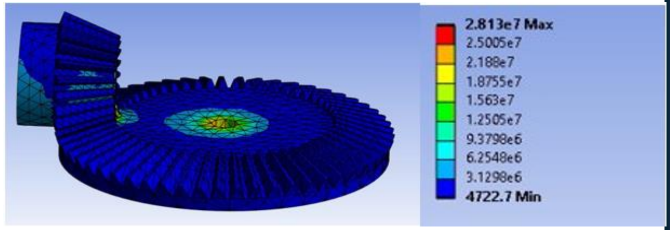


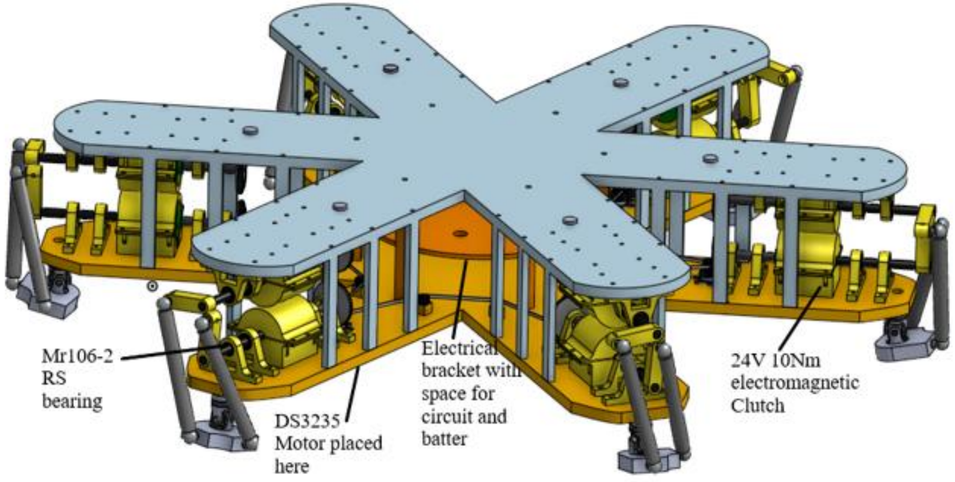
Figure A4: Display of Max EQ stress and strain of Gears



Upper Platform

Anbit Chhetri (1914191)

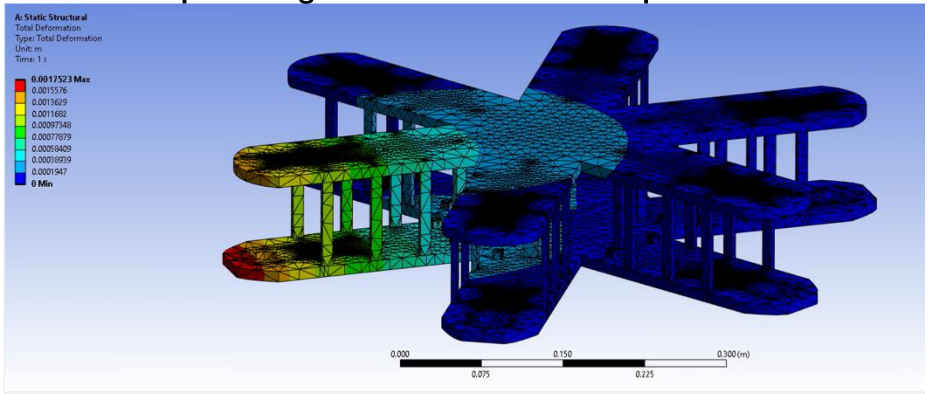
Final Assembly and FEA



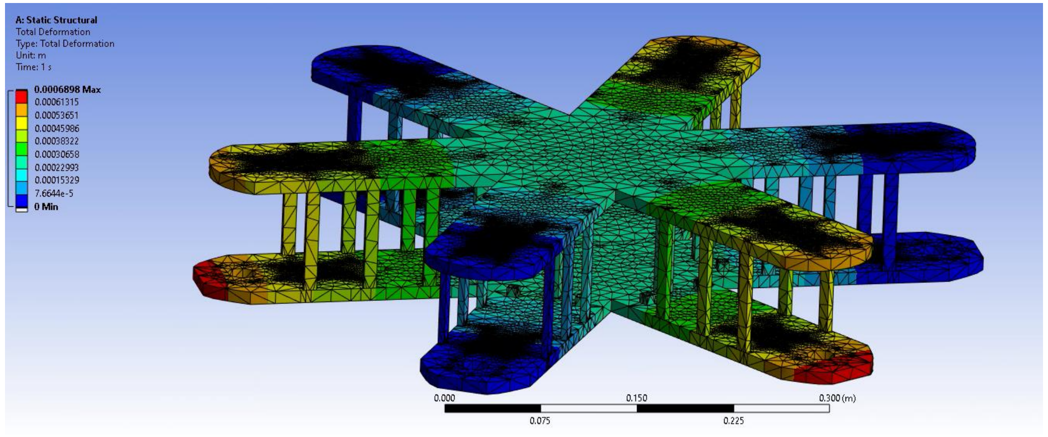
Full Hexapod Design with the electrical component

	Total deformation	EQ Von Misses stress
Case A: 6 legs supporting the frame and leg are stationary.	5.56E-05	3.53E+05
Case B: One leg is raised (can be applied for picking objects or for a wave gait]	1.75E-03	4.93E+06
Case C: 3 legs in opposite sections are raised at the same time.	6.90E-04	5.47E-06

Figure A6: Upper Platform FEA Analysis 3 case studies



Wave Gait FEA simulation / Lift 1 Leg



Tripod Gait FEA simulation

Universal Joint

Huimin Wang (2407446)

Load calculation

Mass calculation： Total mass of Robot （estimate）

$$m_{\text{total}} = m_{\text{upper platform}} + m_{\text{Max carriage weight}} + \left(m_{\text{Universal joint}} + m_{\text{Prismatic link}} + m_{\text{End effector}} + m_{\text{Servo motor}}\right) \times 6$$

$$4.28\,\text{kg} + 10\,\text{kg} + \left(0.0167\,\text{kg} + 0.0181\,\text{kg} + 1.05\,\text{kg} + 0.124\,\text{kg}\right) \times 6$$

$$m_{\text{total}} = 23\,\text{kg}$$

turning force

Force from the upper platform is 4.28*9.8=41.9N

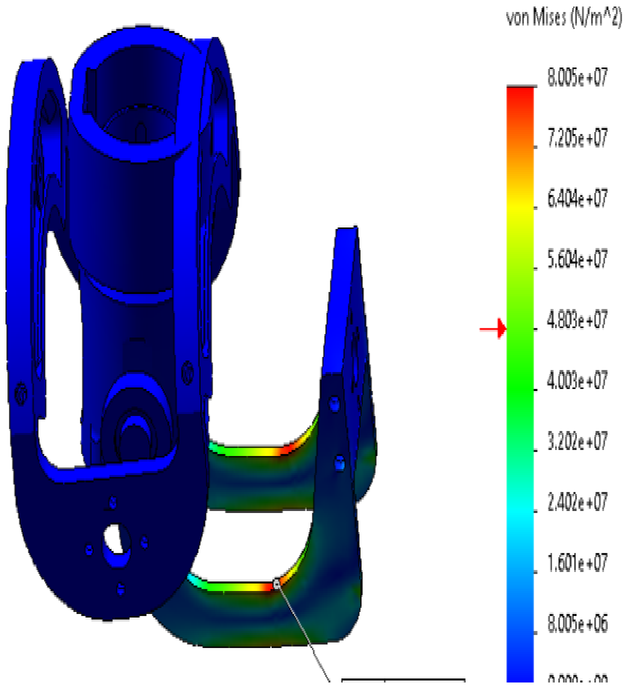
The force from the legs and ee is 23*9.8=225.4N

Universal Joint

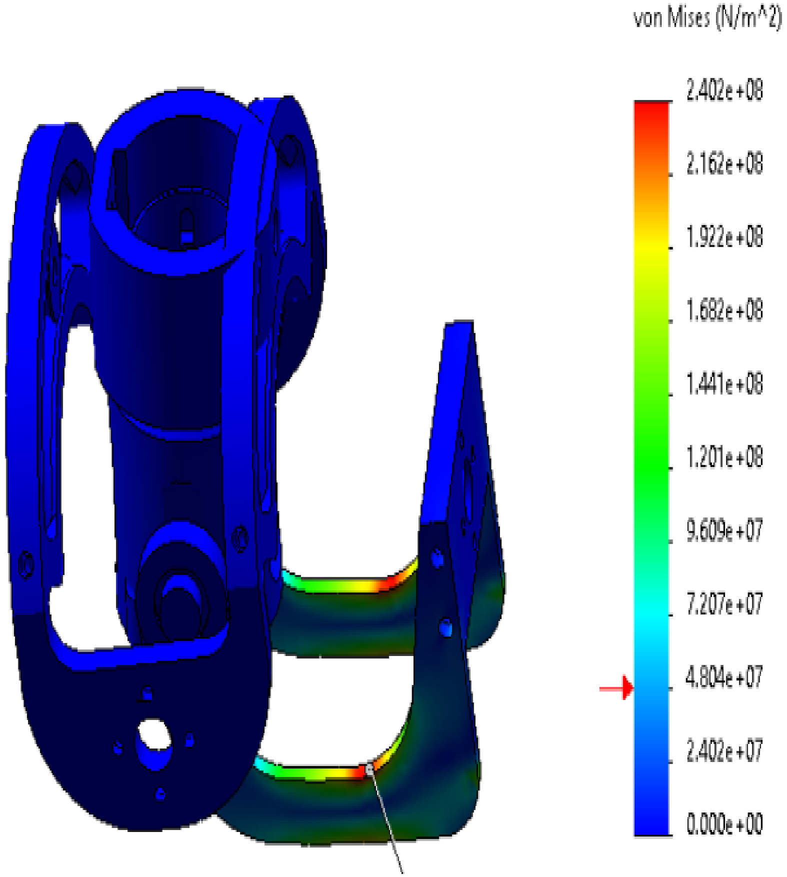
Huimin Wang (2407446)

Results of fea analysis under the original design with raw material as pla

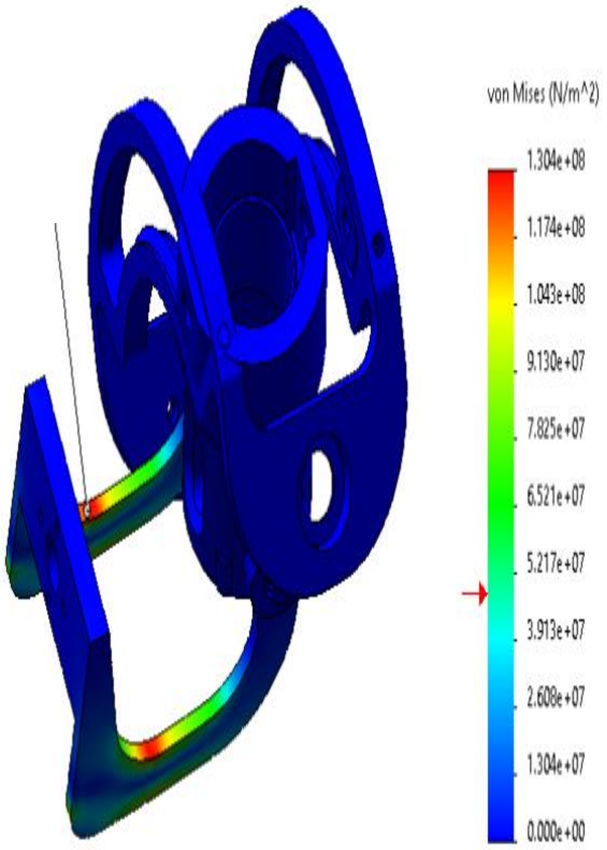
Stress analysis in the case of six-legged standing



Stress analysis for the three-legged standing case



Stress analysis for 45 degree turning angle

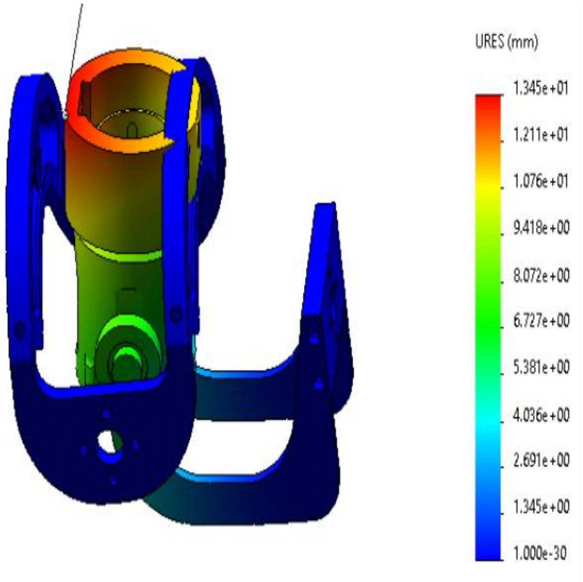


Universal Joint

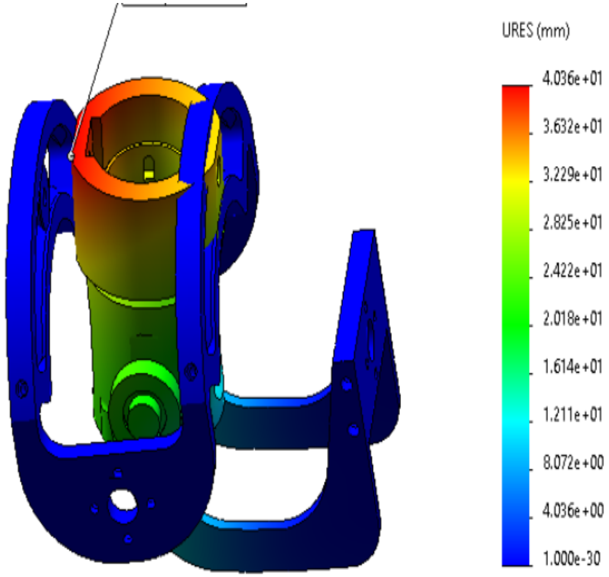
Huimin Wang (2407446)

Displacement before optimisation

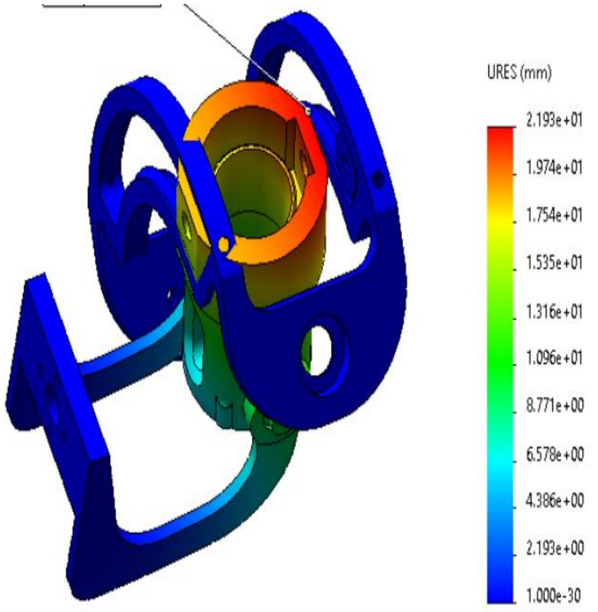
Stress analysis in the case of six-legged standing



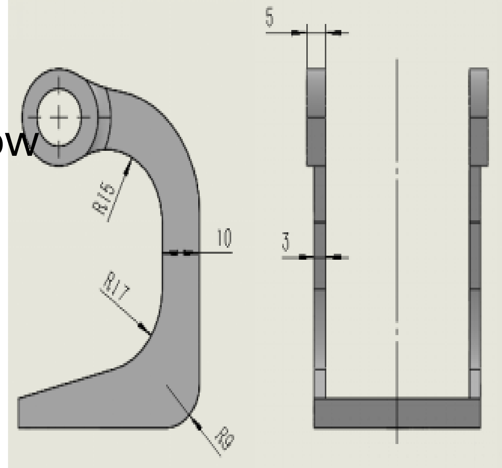
Stress analysis for the three-legged standing case



Stress analysis for 45 degree turning angle



2D of the weak PLACE show2D of the weak PLACE show

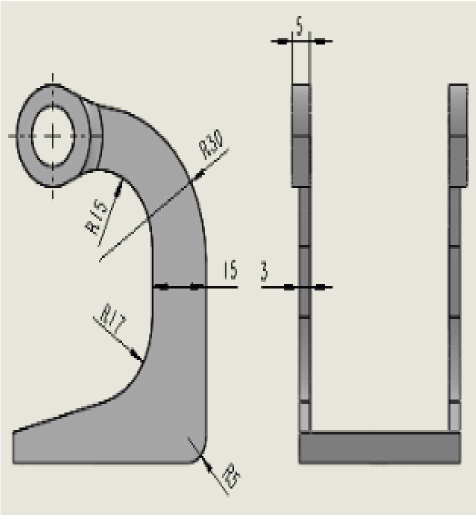


Aim： Optimise weak parts without affecting corners

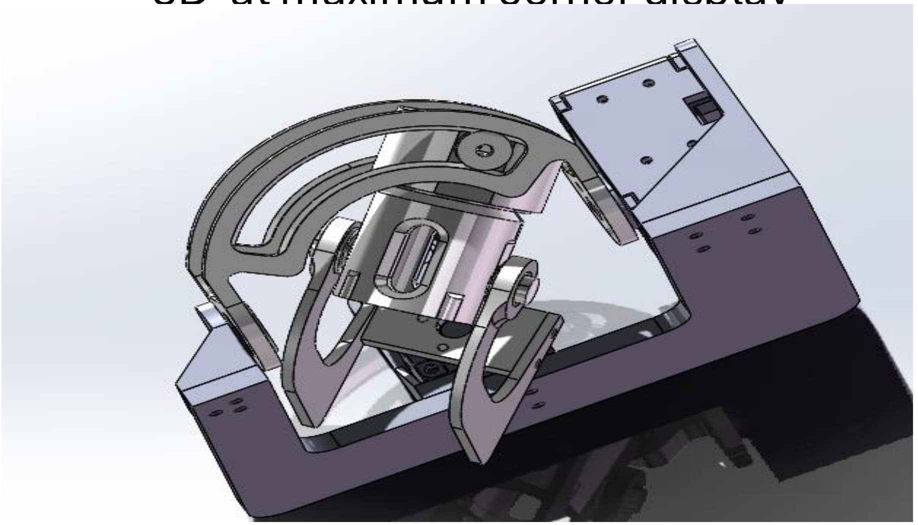
Universal Joint

Huimin Wang (2407446)

Design Optimisation ： Design of optimised 2d



3D at maximum corner display



Material optimisation： AZ31B magnesium alloy

Material properties of PLA and AZ31B

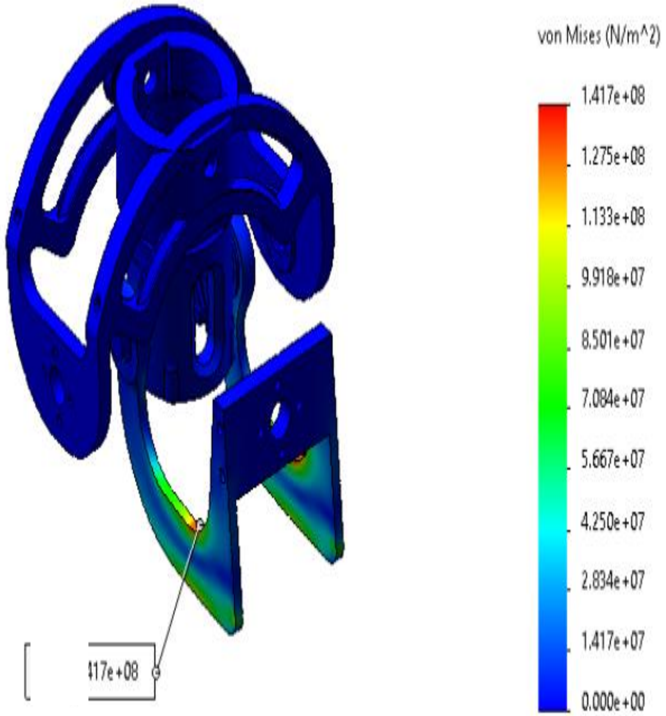
Material	Elastic Modulus (GPa)	Poisson's Ratio	Tensile Strength (MPa)	Yield Strength (MPa)	Elongation at Break (%)	Density KG/m^3
AZ31B	45	0.35	275	220	10	1770
PLA	3.3	0.35	60	48	6	1250
	1264%	358%	358%		67%	41.6%

Universal Joint

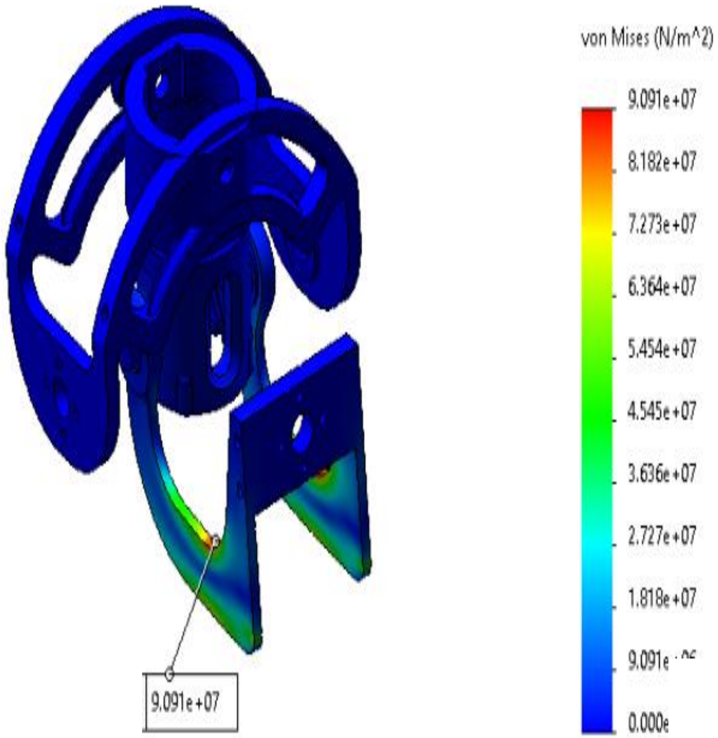
Huimin Wang (2407446)

Stress analysis after design optimisation and after material optimisation

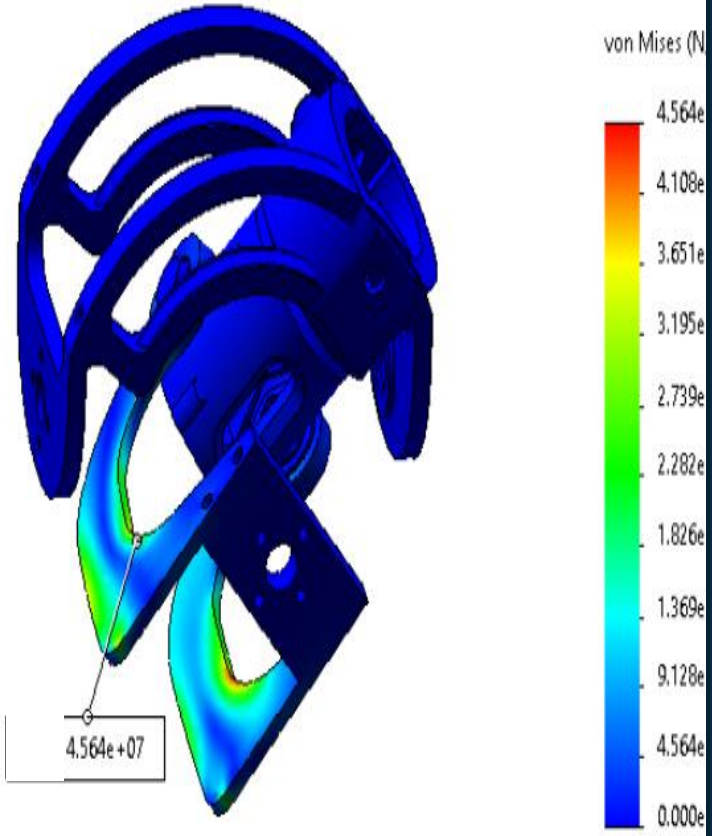
Stress analysis in the case of six-legged standing



Stress analysis for the three-legged standing case



Stress analysis for 45 degree turning angle

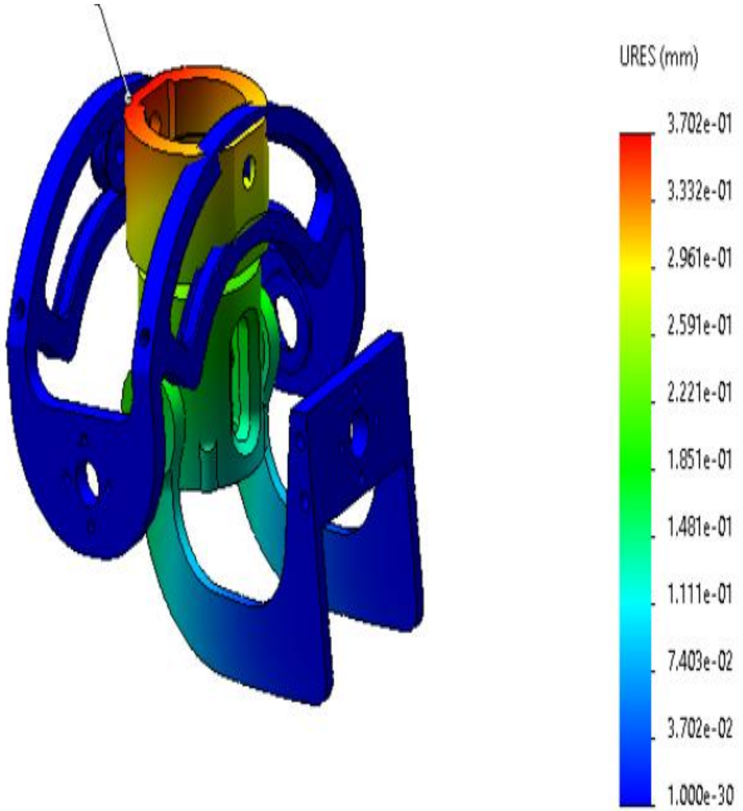


Universal Joint

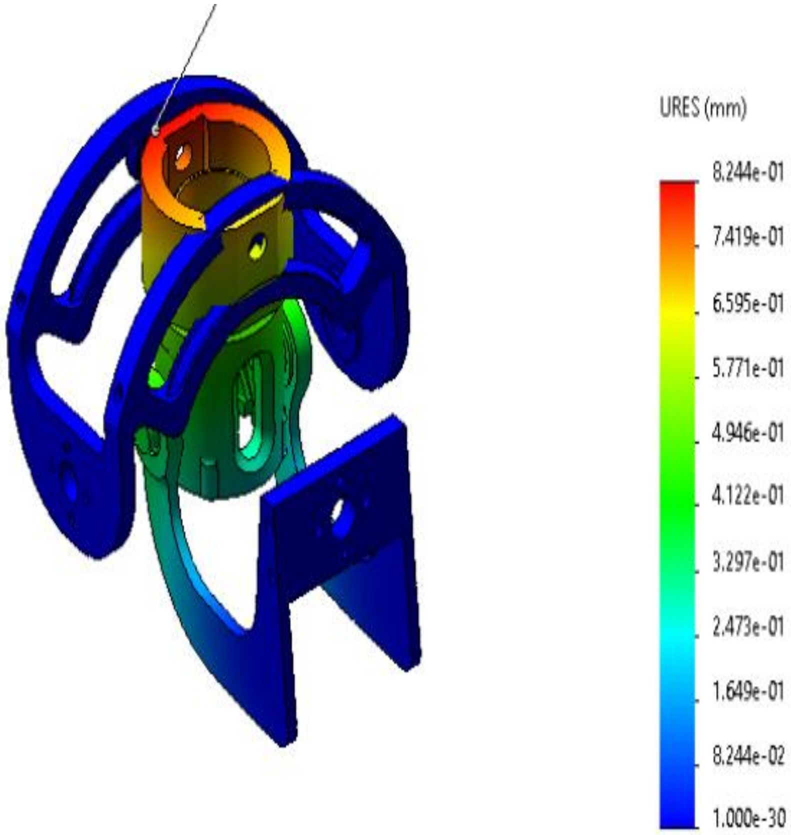
Huimin Wang (2407446)

Optimised displacement

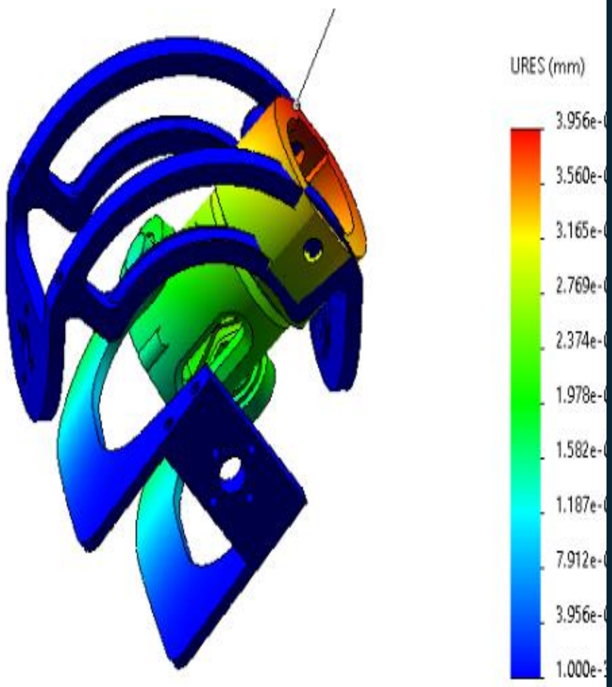
Stress analysis in the case of six-legged standing



Stress analysis for the three-legged standing case



Stress analysis for 45 degree turning angle



Universal Joint

Huimin Wang (2407446)

Comparison of Maximum Stress and Displacement Before and After Optimization (PLA vs. AZ31B)

	Normal Max Stress (MPa)	Normal Max Displacement (mm)	Extreme Max Stress (MPa)	Extreme Max Displacement (mm)	Tilted Max Stress (MPa)	Tilted Max Displacement (mm)
Before Optimization	80.05	13.45	240.2	40.36	130.4	21.93
After Optimization	40.90	0.3702	90.91	0.8244	45.64	0.3956
% Reduction	48.9%	97.2%	48.9%	97.2%	65%	98.2%

Universal Joint

Huimin Wang (240744

Motor section

Parameter	ECX SPEED 22 M	A-max 22	Unit
Nominal Voltage	48 V	15 V	V
Rated Torque	18	6.95	mNm
Stall Torque	420	23.7	mNm
Max Efficiency	91	72	%
Max Allowable Speed	60,000	16,000	RPM
Max Radial Load (5mm flange)	16	7.8	N
Thermal Resistance (Housing–Amb.)	9.5	20	K/W
Bearing Type	Ceramic Ball Bearings	Sleeve Bearings	-
Weight	98	54	g

Prismatic Link

Individual Aim & Objectives

Mingi Choi (2446225)

Aim:

Material selection through material optimisation and develop a 3D printing prototype guideline.

Objectives:

1. Define worst case scenario and load calculation.
2. Material optimisation through FEA results.
3. Decide optimal material for 3D printing prototype.
4. Develop a 3D printing guideline.

Abaqus + WDM

(FEA) **(Material choice & guideline)**

Prismatic Link

Methodology Overview (FEA Setup)

Mingi Choi (2446225)

$$m_{Upper} = \frac{m_{Upper\ platform} + m_{Max,carraige\ weight} + (m_{Universal\ joint} + m_{Servo\ motor}) \times 6}{3}$$

$$m_{Upper} = 5.3kg$$

$$F_{tube,single} = m_{upper} \times g \times SF - \left(F_{axial,cont} \times 0.2\right) + \left(F_{torque,cont} \times 0.2\right)$$

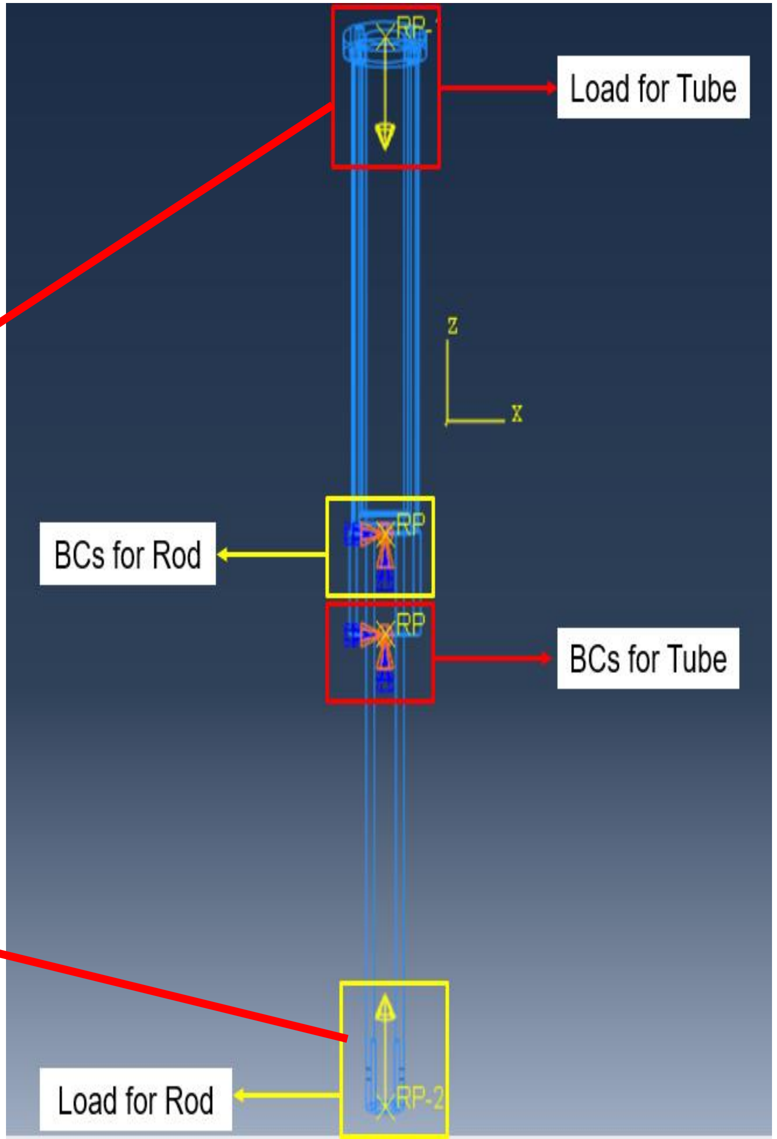
$$= 5.3kg \times 9.81\,m/s^2 \times 2 - (60N \times 0.2) + (65.65N \times 0.2)$$

$$F_{tube,single} = 105N$$

$$F_{rod,single} = \frac{m_{total}}{3} \times g \times SF + \left(F_{axial,cont} \times 0.8\right) - \left(F_{torque,cont} \times 0.8\right)$$

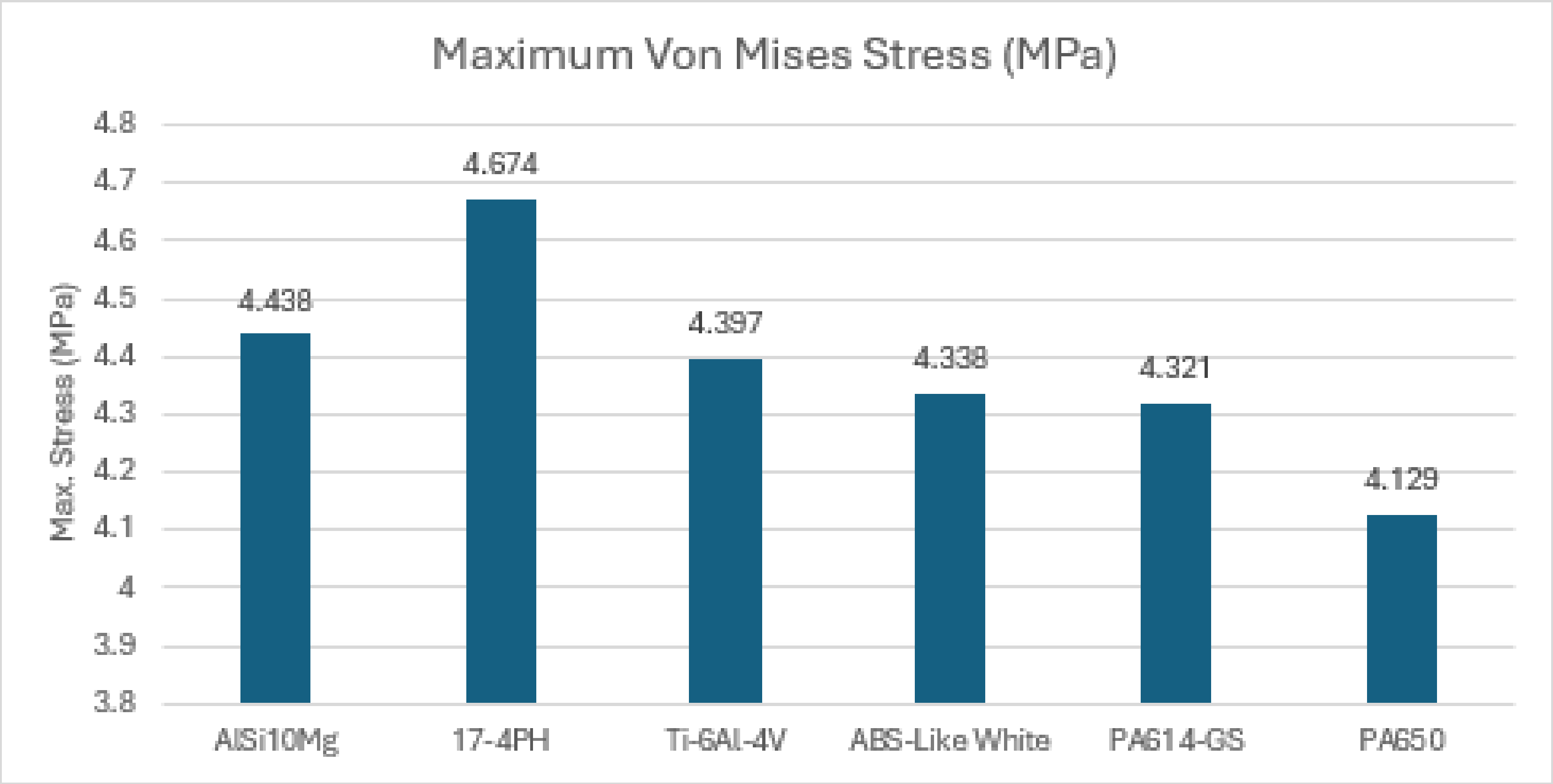
$$= \frac{23kg}{3} \times 9.81\,m/s^2 \times 2 + (60N \times 0.8) - (65.65N \times 0.8)$$

$$F_{rod,single} = 146N$$



Prismatic Link
Results (FEA)

Mingi Choi (2446225)



Prismatic Link

Results (WDM)

Mingi Choi (2446225)

	Stress Resistance	Strain	Mass	Cost Efficiency	Manufacturing Complexity	Total
Weight (%)	30	30	10	20	10	-
AlSi10Mg	5	4	4	3	1	3.8
17-4PH	2	5	1	3	1	2.9
Ti-6Al-4V	2	5	3	1	1	2.7
ABS-Like White	5	1	5	4	4	3.5
PA 614-GS	5	1	5	5	3	3.6
PA 650	4	1	5	5	3	3.3

Prismatic Link

3D Prototype Guideline

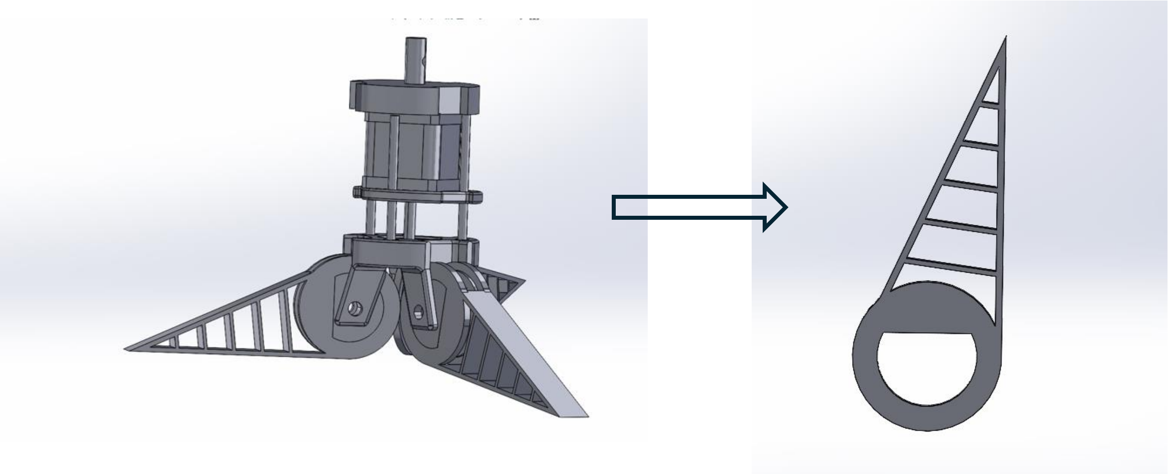
Mingi Choi (2446225)

1. Materials exhibiting a maximum displacement exceeding 10 mm should be avoided.
2. Only materials demonstrating a total strain of 10% or less should be considered as final candidates.
3. Stress resistance and strain should be prioritized as the primary selection criteria.
4. Cost and manufacturing complexity should be used only as secondary decision criteria.
5. If polymeric materials are utilized, the following conditions must be met:
   - Maximum displacement of 15 mm or less.
   - Strain of 10% or less.
   - Structural reinforcement and composite design strategies must be implemented in conjunction.
6. AlSi10Mg represents the most suitable choice among metallic materials.
7. Decisions should not be made solely based on WDM results (scores).

End Effector

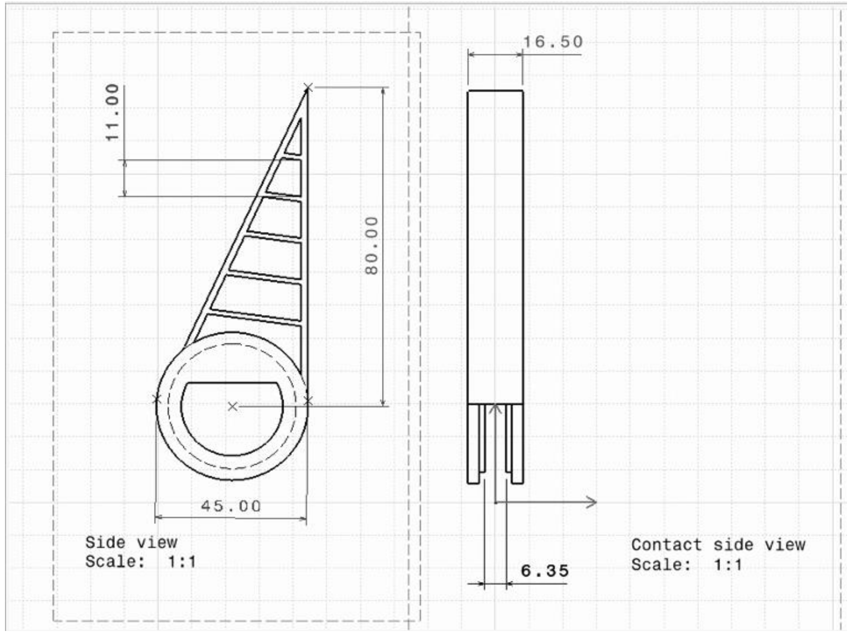
Hamza Al-Siyabi (2429643)

Aims and Objectives



Aim:
To optimize the structural performance of a Fin Ray-inspired end effector for grasping in a hexapod robot using Finite Element Analysis (FEA).

Objectives:
- Design 12 Fin Ray finger variations by modifying rib angle and wall thickness.
- Simulate grasping behaviour using ANSYS.
- Compare performance based on tip displacement, contact area, and reaction force.
- Assess the effect of material stiffness (TPU A85 vs TPU A95).
- Identify the best design for adaptive, efficient gripping.



End Effector

Hamza Al-Siyabi (2429643)

Methodology

DESIGN:

12 FIN RAY FINGER VARIATIONS MODELLED IN CATIA (RIB ANGLE & WALL THICKNESS CHANGES).

SIMULATION:
CONDUCTED IN ANSYS WITH A 1 NM TORQUE APPLIED AT THE FINGER BASE.

OBJECT PLACEMENT:

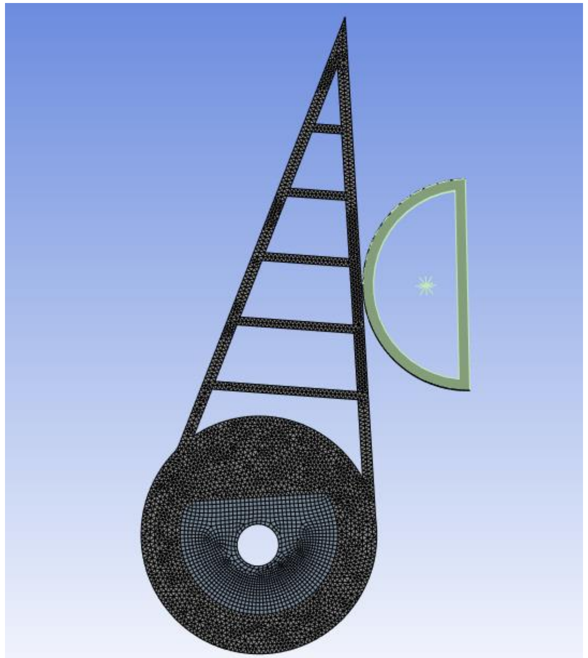
A RIGID SEMI-CIRCULAR OBJECT (⌀ 40 MM) PLACED 50 MM IN FRONT OF THE FINGER TO SIMULATE CONTACT.

MATERIALS TESTED:
TPU A85 (FLEXIBLE) AND TPU A95 (STIFFER).

PERFORMANCE METRICS:

TIP DISPLACEMENT, CONTACT AREA, AND REACTION FORCE AT THE BASE.

Variation	Contact side thickness	Opposite side thickness	Rib Angle (°)
Initial model	2 mm	2 mm	0°
Variation 1	2 mm	2 mm	-15°
Variation 2	2 mm	2 mm	+15°
Variation 3	2 mm	2 mm	+30°
Variation 4	2.5 mm	2 mm	0°
Variation 5	3 mm	2 mm	0°
Variation 6	2 mm	2.5 mm	0°
Variation 7	2 mm	3 mm	0°
Variation 8	2.5 mm	2 mm	+15°
Variation 9	3 mm	2 mm	+15°
Variation 10	2 mm	2.5 mm	+15°
Variation 11	2 mm	3 mm	+15°



End Effector

Hamza Al-Siyabi (2429643)

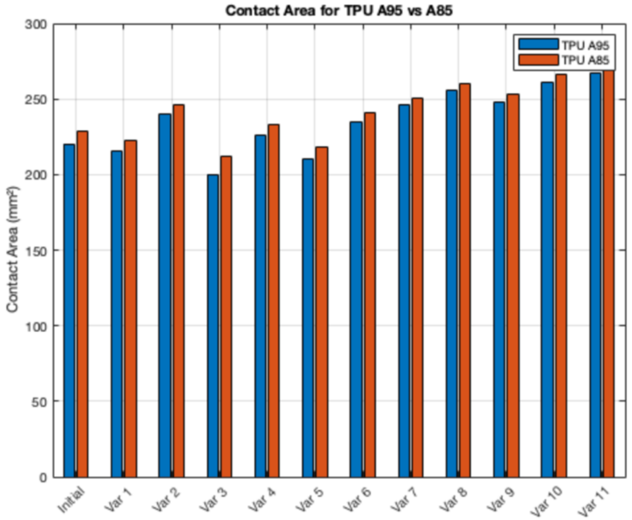
Results and discussion

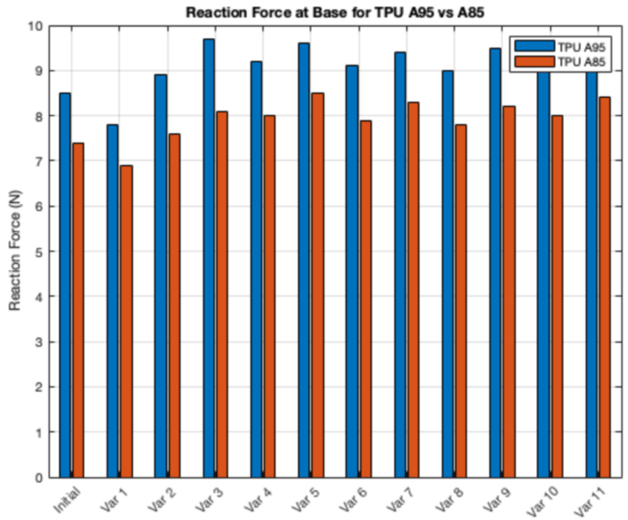
TPU A95:
Higher reaction force, lower deformation, ideal for load-bearing and support.

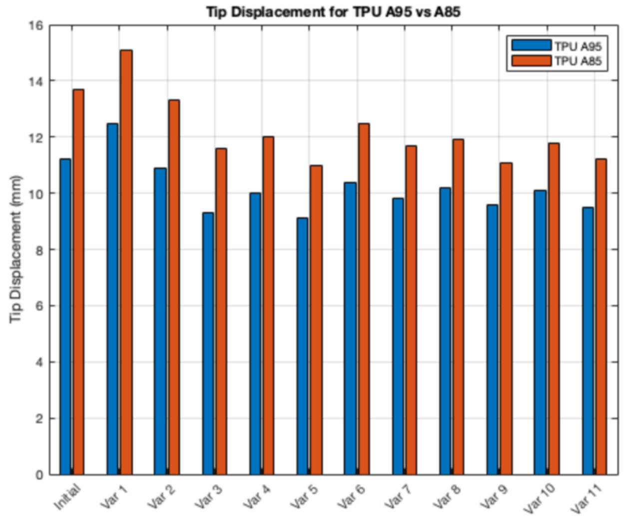
TPU A85:
Greater flexibility and contact area, better for delicate object handling.

Key Insights:

- A +15° rib angle improved adaptability and grip strength.
- Asymmetrical wall thickness boosted structural support and contact efficiency.
- Optimal design showed ~21% better contact area and up to 18% less tip displacement than the baseline.







Rank	Variation	Key Specs (Contact/Opposite/Rib)
1st	Variation 11	2 mm / 3 mm / +15°
2nd	Variation 10	2 mm / 2.5 mm / +15°
3rd	Variation 9	3 mm / 2 mm / +15°

Gait Simulation and Terrain-Aware Design

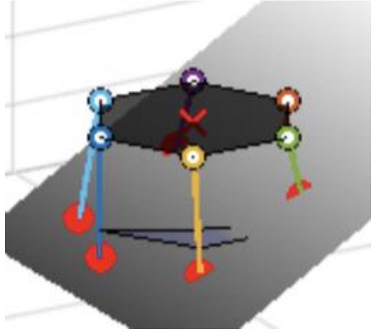
Roro Mohammadi 2107729

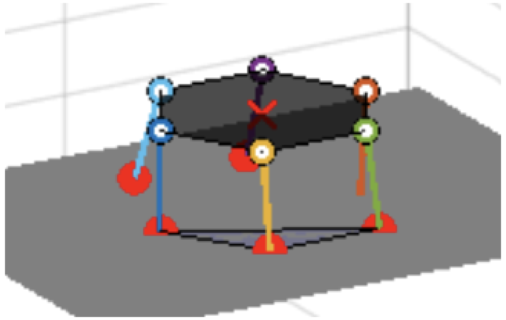
- Simulate ripple, wave, and reduced-leg gaits (crawl)

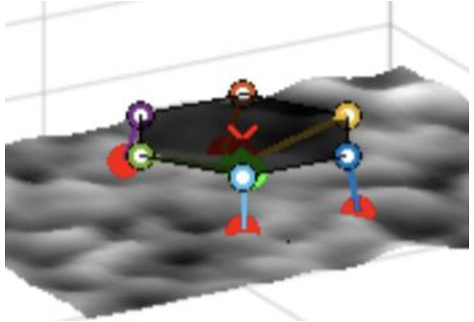
- Test Energy and Stability metrics across:
  - flat terrain
  - Inclined terrain
  - rough terrain

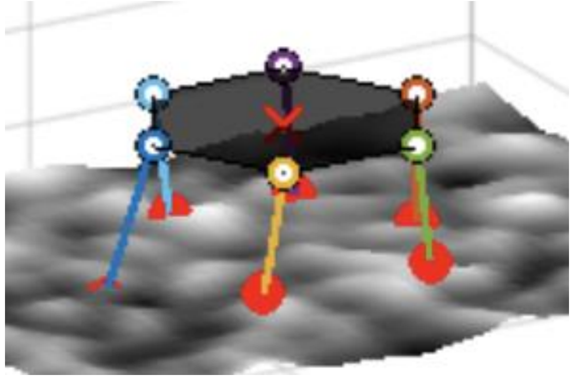
- Implement adaptive offset control as well as stance leg widening for CoM stability (like a spider)

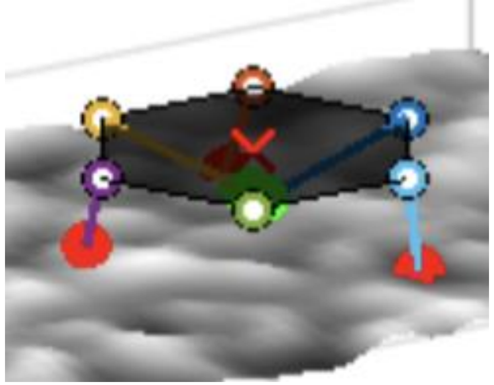
- Implemented teams real design parameters in simulation to assist team with design limits.
  - Leg lengths
  - Platform size











Gait Types and Why They Matter

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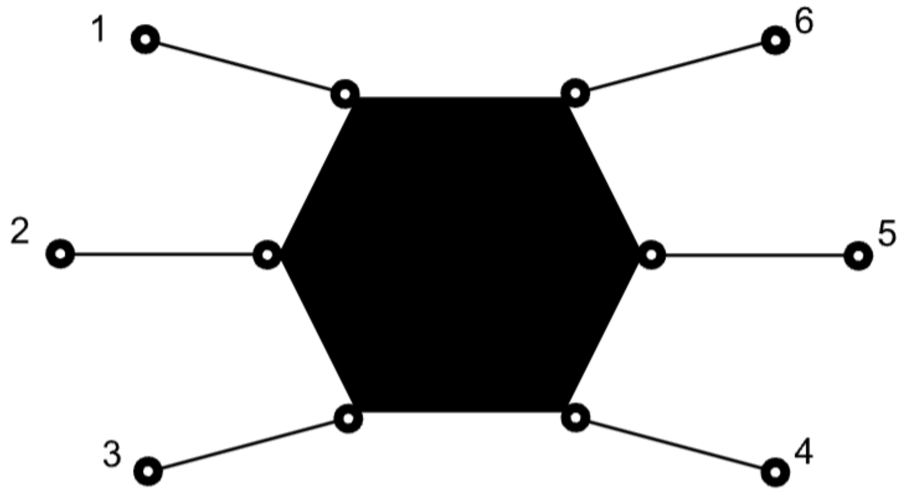
- **Each gait has its benefits**
  - **Ripple Gait - ** sequentially (e.g., 1 → 2 → 3 → …)
    - Balanced energy and stability
    - Great for flat and slightly inclined terrains
  - **Tripod Gait - ** 3 legs at a time, A (1,3,5), B (2,4,6)
    - Fastest Gait
    - Respectively lower stability
      - Big CoM shifts
  - **Wave Gait** (Only one leg swings at a time)
    - Maximum stability but slowest gait
      - Fewer sudden shifts in CoM
    - Handles rough/uneven terrains
  - **Crawl Gait**
    - 2-3 legs holding object
      - central loaded
    - The rest walk sequentially
      - 2-3 legs on ground all times



Gait	Stability	Speed	Energy Use	Best For
Ripple	Moderate	Moderate	Moderate	Versatile terrain; general-purpose locomotion
Wave	Very High	Very Low	Moderate	Rough terrain; high-stability tasks
Tripod	Low	High	Moderate–High	Fast movement on flat, predictable surfaces
4-Leg Crawl	Low	Low–Moderate	Low	Payload support; object-holding while moving
3-Leg Crawl	Very Low	Very Low	Very Low	Static holding; minimal actuation; limp scenarios

Effective Stability Margin Calculation

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Stability was measured using:

$$S = \frac{\min(d_i)}{h_{CoM}}$$

where:

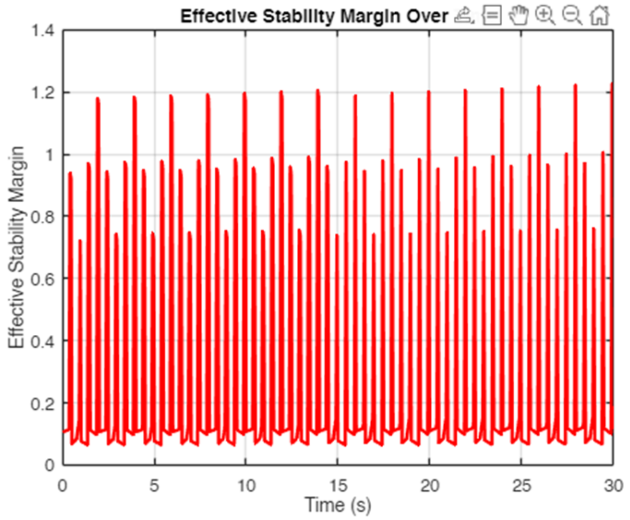
- d_i : shortest distance from the projected CoM to the edge of the stance polygon
- h_{CoM} : height of the center of mass above terrain

Support Polygon Calculation:

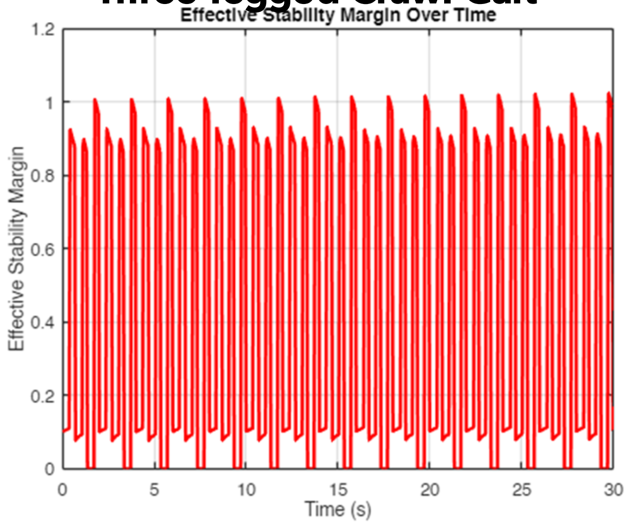
- Calculated using the **convex hull** of the stance leg contact points
- Implemented in real-time using MATLAB's convhull() function on 2D (x,y) foot positions

- Adaptive offset triggered when S < 0.7

Four-legged Crawl Gait



Three-legged Crawl Gait



Effective Stability Margin Calculation

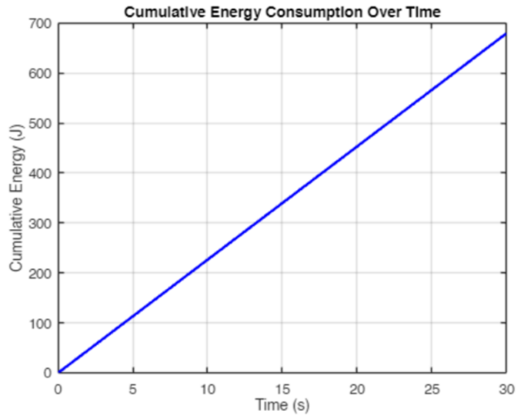


Figure 5.3.3: Cumulative energy consumption over time

Two-Part Model

- **Swing Phase (Shoulder Motor)**

$$E_{swing} = \frac{(\tau_{static} + \tau_{inertial}) \cdot \nu_{swing} \cdot \Delta t}{\eta_{shoulder}}$$

$\tau_{static} = mgl$ (torque to hold leg mass), $\tau_{inertial} = I \cdot a$ (acceleration torque), ν_{swing} : angular speed, $\eta_{shoulder}$: shoulder motor efficiency

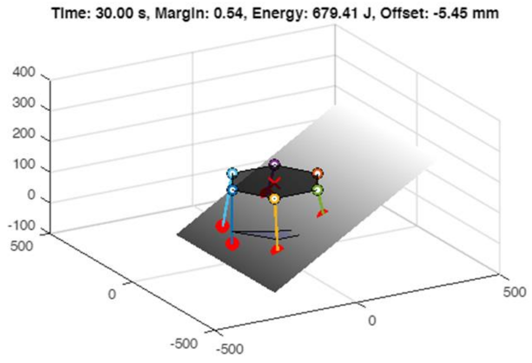
4-legged and 3-legged scenarios have an extra 5kg object to hold

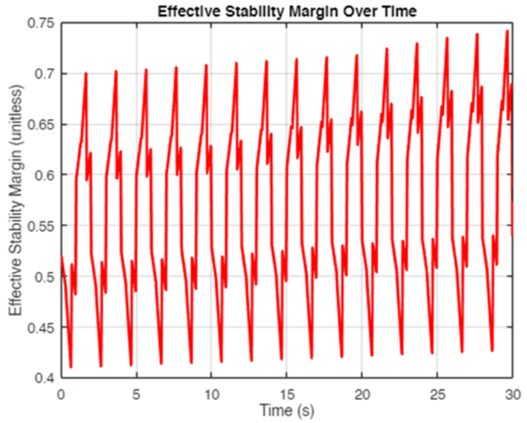
- **Stance Phase (Prismatic Actuator)**

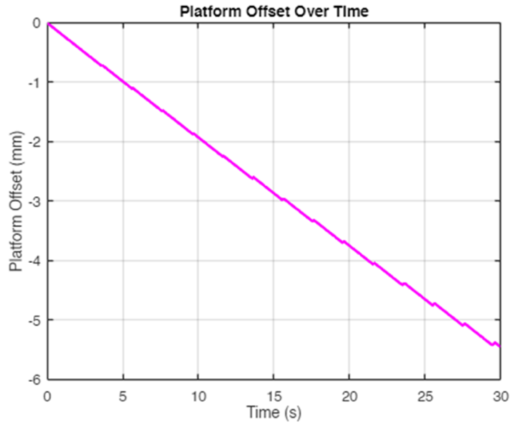
$$T_{motor} = \frac{F_{leg} \cdot p}{2\pi \cdot \eta_{headscrew}} \qquad \omega_{motor} = \frac{2\pi \cdot v_{leg}}{p}$$

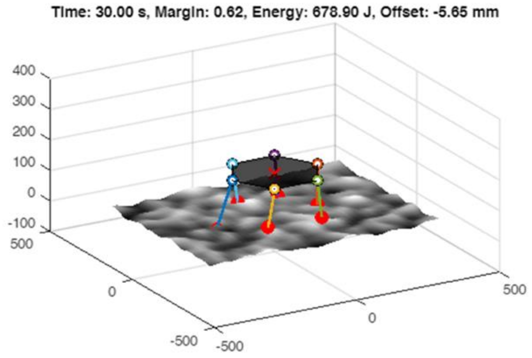
$$P = \frac{T_{motor} \cdot \omega_{motor}}{\eta_{gearhead}} \qquad E_{prismatic} = P \cdot \Delta t$$

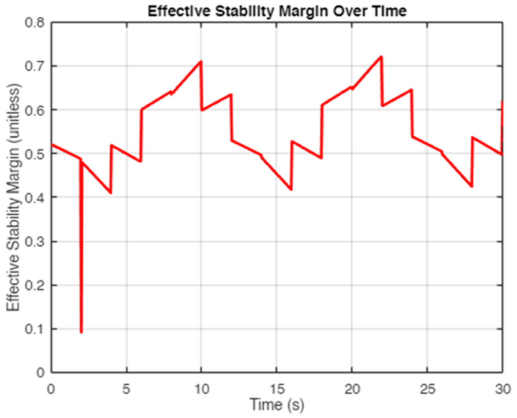
Where F_{leg} is the force on a stance leg (computed via load sharing), p is the leadscrew pitch, and η values are efficiency terms.

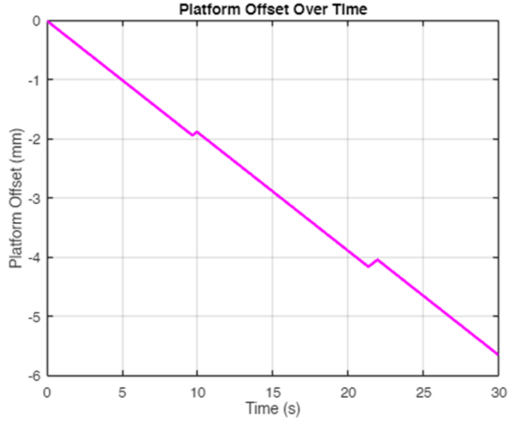

Time: 30.00 s, Margin: 0.54, Energy: 679.41 J, Offset: -5.45 mm


Effective Stability Margin Over Time
Effective Stability Margin (unitless)
Time (s)


Platform Offset Over Time
Platform Offset (mm)
Time (s)


Time: 30.00 s, Margin: 0.62, Energy: 678.90 J, Offset: -5.65 mm


Effective Stability Margin Over Time
Effective Stability Margin (unitless)
Time (s)


Platform Offset Over Time
Platform Offset (mm)
Time (s)

Gait–Terrain Summary Table

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Scenario	Stability	Energy (J)	Final Offset (mm)
Flat - Ripple	0.57	679.41	−5.49
Inclined - Ripple	0.58	679.41	−5.45
Rough - Wave	0.55	678.90	−5.65
Four-Legged	0.45	134.42	−4.25
Three-Legged	0.40	127.63	−1.35

- Flat and Inclined Terrain
  - moderate Stability
  - Moderate energy usage (Ripple Gait)
- Rough Terrain
  - 6 legs
    - Surprisingly moderate stability despite terrain variances
    - Lower energy usage compared to other 6-legged scenarios
  - 4-Legged
    - Lower stability but lower energy usage too due to only 4 legs and lower initial leg length
  - 3-Legged
    - Lowest stability and lowest energy due to lowest support legs

Commercial Impact, Social and Environmental Imapct

Commercial Impact

- **Research & Education:** Modular design ideal for academic labs, teaching mechatronics, and simulation-led prototyping.
- **Surveillance & Security:** Terrain-adaptive design suitable for hazardous zone patrols with reduced-leg mobility.
- **Agriculture & Automation:** Great for greenhouse monitoring and tool manipulation in uneven terrains.
- **Startup Platform:** Easily reconfigurable base for industrial inspection, sorting, or delivery robots.
- **Cost Efficiency:** Uses DMLS friendly materials (AlSi10Mg) and off-the-shelf Maxon actuators, supports low-cost production and scalability.

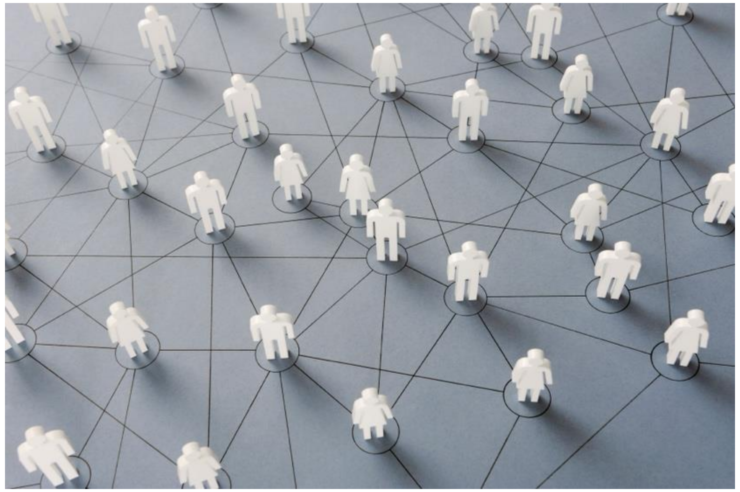
Environmental Impact

- **Material Efficiency:** Additive manufacturing reduced waste during prototyping.
- **Energy Optimisation:** Wave gait consumes less power on rough terrain—critical for autonomous missions.
- **Eco-Conscious Materials:** Use of recyclable AlSi10Mg and thermoplastics like TPU.
- **Repairability:** Modular joints allow easy replacements instead of full leg disposal—extends life cycle.
- **Simulation-Led Design:** Fewer physical prototypes mean a smaller carbon footprint.

Commercial Impact, Social and Environmental Imapct

Social Relevance & Technological Accessibility

- **STEM Accessibility:** CAD models, simulations, and modular design ideal for student projects and competitions.
- **Disaster Response:** Fault-tolerant gait and electromagnetic clutch system support operations in post-disaster zones.
- **Remote Operations:** Useful for inspection tasks in areas like mines, nuclear plants, or offshore rigs.
- **Example Use Case:** Post-Fukushima recovery—hexapod could carry sensors and navigate rubble with reduced-leg gaits.



Technical Challenges & Overcome

Software

Skill Difference

Cooperation + Outer Source

Compatibility

'.STEP' file

Key recommendations for further work

- **Gait Simulation & Control**
  - Implement adaptive gait transitioning using real-time sensor feedback to optimise stability and energy use on varied terrain.
- **Prismatic Link**
  - Conduct high-fidelity FEA with true boundary and friction conditions to validate dynamic performance under motor-driven loads.
- **Universal Joint (Shoulder)**
  - Prototype and test under compound loading to validate FEA and assess displacement under real gait transition scenarios.
- **End Effector (Fin Ray Gripper)**
  - Perform dynamic walking impact tests to evaluate grip durability and structural response under gait-induced forces.
- **Upper Platform & Integration**
  - Run full system integration tests to verify structural and control compatibility under operational loading.

IMU (platform), foot sensors and potentiometers (joint positions)

Questions

Brunel University of London ME5692 Group Project Supervised by Dr. Mingfeng Wang