Selin Rabia Kinsiz 122207037

Serra Lal Tosun 123207041

Yağız Gelen 122207048

Emir Eren 122207095

A Report Submitted to the

Mechatronics Engineering Department of

In MECA 321 Mechanics of Material

İstanbul Bilgi University

Table of Contents

1. Design Requirements and Assumptions 3
   1.1 Design Requirements 3
   1.2 Assumptions 3
2. Conceptual Design 4
   2.1 Configuration and Degrees of Freedom (DOF) 4
   2.2 Structural Optimization and Material 4
   2.3 Assembly and Joint Design 4
3. CAD Design (SolidWorks) 5
   3.1 Modeling Methodology 5
   3.2 Assembly and Constraints 5
   3.3 Material Assignment and Mass Properties 6
4. Material and Cross-Section Selection 6
   4.1 Cross-Section Selection: Industrial I-Beams 7
5. Structural Analysis for Static Failure 7
   5.1 FBD 7
   5.2 V-M Diagrams 11
   5.3 Graphs of V-M Diagrams 14
   5.4 Bending Stress 15
   5.5 Pin Shear Stresses 16
   5.6 Bearing Stresses 16
   5.7 Max Deflection 17
   5.8 Buckling Calculations 18
6. Simulation Results 19
   6.1 Stress Results 19
   6.2 Strain Results 19
   6.3 Displacement Results 20
   6.4 Factor of Safety Results 20
7. Design Iteration and Optimization 20
8. Cost Analysis 22
9. Distribution of Project Responsibilities 22
10. Conclusions 23
AI Usage Statement 23
References 24

1. Design Requirements and Assumptions

1.1 Design Requirements

- **Payload Capacity:** The robotic arm is designed to lift a payload of **50 kg** located **2 meters** away from its base.
- **Safety Standards:** A minimum Factor of Safety (FOS) of **2** is targeted for all structural components to prevent static failure.
- **Structural Geometry:** Industrial standard profiles (**I beams**) are utilized for the arm links to optimize the strength to weight ratio and ensure manufacturability.
- **Component Assembly:** The design incorporates a combination of **solid and hollow cylindrical pins** of varying dimensions for joint assemblies, selected to optimize weight and structural integration.

1.2 Assumptions

- **Material Properties:** The material (HDPE) is assumed to be isotropic and homogeneous. Constant properties (Elastic Modulus: 1.07 GPa, Yield Strength: 22 MPa) are applied throughout the volume.

- **Geometric Profile:** The arm links are modeled using **standard industrial I beam profiles** to optimize the strength to weight ratio, in accordance with the design requirements.

- **Static Loading:** The payload of 50 kg is applied as a static force. Dynamic effects such as angular acceleration, inertia forces during movement, and vibrations are not included.

Boundary Conditions: The base of the robot is fixed at the **bottom face**, assuming a perfectly rigid installation surface with zero degrees of freedom.

Linear Elasticity: The analysis assumes linear elastic material behavior. Nonlinear effects such as plasticity, time dependent deformation, or large displacement non linearities are neglected for this static study.

Thermal Conditions: The analysis is conducted at standard room temperature (approx. 20-25°C). Thermal expansion or softening of the HDPE material is not considered.

2. Conceptual Design

The proposed robotic arm is designed as a **multi segment serial manipulator**. Specifically engineered to lift a **50 kg payload** at a maximum reach of **2 meters**. The design balances structural strength and weight efficiency. It utilizes a step-down linkage strategy to minimize the moment of inertia and stress on the base joints.

2.1 Configuration and Degrees of Freedom (DOF)

The robotic arm consists of a series of rigid links connected by rotational joints. The configuration is arranged to provide the necessary workspace and control for the lifting task. The design features the following primary segments:

- **Base & Body:** Provides a rigid foundation and vertical difference.
- **Serial Linkages:** The arm utilizes a successive arrangement of links that decrease in size and mass from the shoulder to the end effector. This configuration allows for a fully extended "worst case" reach while maintaining stability.

2.2 Structural Optimization and Material

To satisfy the design requirements, the arm links are designed with standard I beam profiles

- **Mass Distribution Strategy:** As seen in the design data, the mass of the links is progressively reduced (from approx. **13.5 kg** for the first link to **1.5 kg** for the final link). This " decreasing" strategy significantly reduces the bending moment applied to the root joints and optimizes the center of mass location.
- **Material: High Density Polyethylene (HDPE)** is selected as the primary structural material (E = 1.07 GPa), offering a high strength to weight ratio crucial for this multi-link setup.

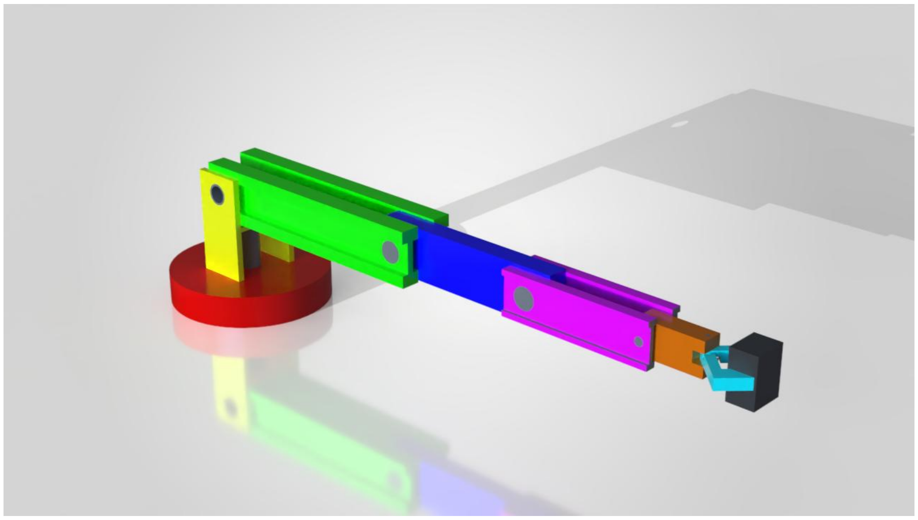
2.3 Assembly and Joint Design

The mechanical integration of the segments is achieved using a specifically calculated pin system.

- **Pin Selection:** The assembly incorporates a hybrid approach using both **solid pins** and a **hollow pin**.
- **Function:** Hollow pins are utilized in lower stress joints to further reduce the total weight, while solid pins are kept for critical load bearing joints, ensuring the design meets the safety factor requirements.

3. CAD Design (SolidWorks)

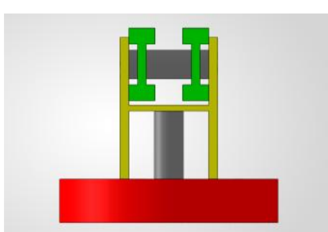
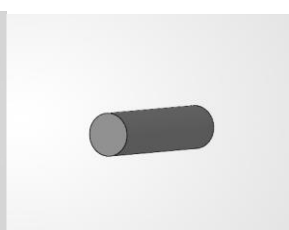
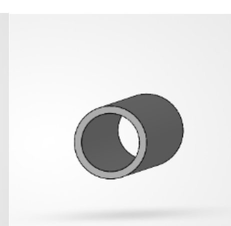
The complete 3D geometric model of the robotic arm was developed using **SolidWorks** software, sticking to the project requirements for solid modeling and parametric design.



3.1 Modeling Methodology

The design process began with the creation of individual components representing the base, vertical body, and the four arm segments.

- **Part Creation:** Each link was modeled by sketching the cross-sectional profiles and using extrusion features to generate the 3D geometry. As specified in the conceptual design, the links were shaped to resemble **I beam profiles** to optimize rigidity.
- **Pin & Connection Modeling:** Specific connection pins were modeled as separate components. A combination of **solid and hollow cylindrical pins** was created to accurately represent the physical assembly and mass distribution.

3.2 Assembly and Constraints

The individual parts were integrated into a final assembly file (.SLDASM) using standard mating conditions.

- **Joint Constraints:** Centered and aligned mates were applied between the link holes and the connecting pins to define the proper alignment of the revolute joints.
- **Configuration:** For the design validation, the assembly was constrained in a **fully extended horizontal position**. This configuration represents the "worst case" scenario where the moment arm is longest (2 meters), ensuring that following analyses cover the most critical loading condition.

3.3 Material Assignment and Mass Properties

To ensure accurate physical simulation, the material properties of **High-Density Polyethylene (HDPE)** were assigned to all structural components within the SolidWorks environment.

- **Mass Calculation:** Using the "Mass Properties" tool, the weight of each component and the center of gravity (COG) of the entire assembly were calculated. The payload was modeled by main the mass properties of the end effector load to **50 kg**, simulating the target lifting capacity.

4. Material and Cross-Section Selection

This section outlines the reason behind the selection of materials and geometric profiles used in the robotic arm. The choices were driven by the design objectives of minimizing weight while ensuring sufficient stiffness to support the 50 kg payload.

Table 1: Material properties assigned to the robotic arm components

Component	Material	E (GPa)	Yield Strength (MPa)	Density (kg/m³)
Base	High-Density Polyethylene	1.07	22	960
Body	High-Density Polyethylene	1.07	22	960
Arm_1	High-Density Polyethylene	1.07	22	960
Arm_2	High-Density Polyethylene	1.07	22	960
Arm_3	High-Density Polyethylene	1.07	22	960
Arm_4	High-Density Polyethylene	1.07	22	960
Gripper	High-Density Polyethylene	1.07	22	960

Cylinder	High-Density Polyethylene	1.07	22	960
Pim_Hole	High-Density Polyethylene	1.07	22	960
Pim_1.2	High-Density Polyethylene	1.07	22	960
Pim_2.3	High-Density Polyethylene	1.07	22	960
Pim_3.4	High-Density Polyethylene	1.07	22	960
Pim_Gripper	High-Density Polyethylene	1.07	22	960

4.1 Cross-Section Selection: Industrial I-Beams

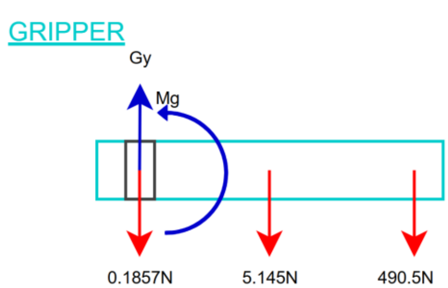
In accordance with the design requirements to use industrial standard profiles, the arm links are modeled with I beam cross-sections.

- Geometric Advantage: The I beam geometry places most of the material mass (flanges) away from the neutral axis. This significantly increases the Area Moment of Inertia (I) relative to the cross-sectional area.
- Bending Resistance: Since the primary failure mode for the horizontal arm is bending due to the vertical payload, the high moment of inertia provided by the I beam profile offers higher resistance to deflection compared to solid rectangular bars of equal weight.

5. Structural Analysis for Static Failure

In this section, the structural behavior of the robotic arm under static loading is evaluated. By applying the design loads to the HDPE structure, both analytical and numerical methods were used to calculate maximum stress and deflection. The results presented below demonstrate the comparison between theoretical expectations and simulation outputs, ensuring the design meets the minimum Factor of Safety criteria.

5.1 FBD



Gripper

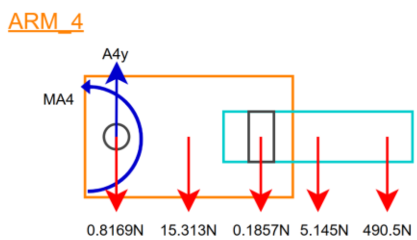
CW = $-$

CCW = $+$

$\sum F_y = 0$, $G_y = +495.837$

$\sum M_G = 0$, $M_G = 0.46 + 72.834$

$M_G = +73.294Nm$



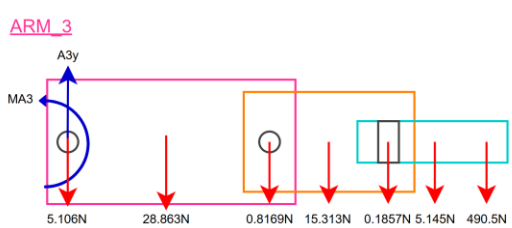
Arm4

$A_{4y} = +511.960N$

$M_{A4} = (15.313 \times 0.07852) + (5.145 \times 0.151792) + (490 \times 0.328119) + (0.1857 \times 0.18)$

$M_{A4} = 1.202 + 0.781 + 161.124 + 0.033$

$M_{A4} = 163.140N\mathrm{m}$



Arm3

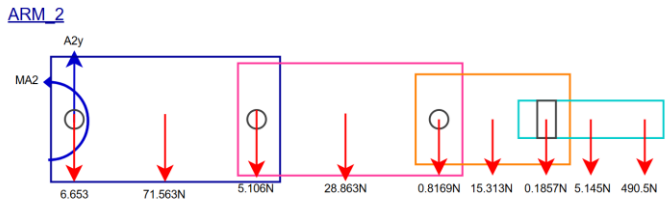
$A_{3y} = 510.958 + 28.853$

$A_{3y} = 545.9396N$

$M_{A3} = (0.19365 \times 28.863) + (0.49035 \times 15.313) + (0.68122 \times 5.145) + (0.74032 \times 490.5) + (0.1857 \times 0.59183) + (0.8169 \times 0.41183)$

$M_{A3} = 5.589 + 7.509 + 3.505 + 363.127 + 0.1099 + 0.3364$

$M_{A3} = 380.176 Nm$



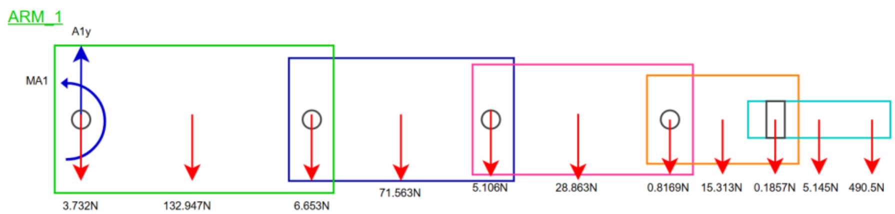
Arm2

$A_{2y} = 539.821 + 71.563$

$A_{2y} = 624.1456 N$

$M_{A2} = 18.774 + 20.733 + 15.543 + 6.204 + 620.483 + 0.207 + 0.765 + 2.6789$

$M_{A2} = 685.3879 Nm$



Arm1

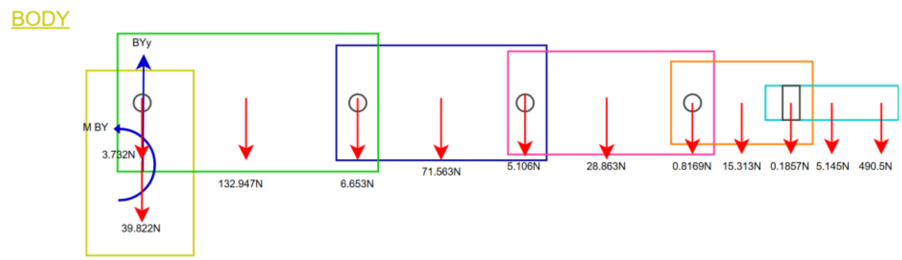
$A_{1y} = 611.384 + 132.947$

$A_{1y} = 760.8244 N$

$M_{A1} = (0.39385 \times 132.947) + (1.0234 \ \times 71.563) + (1.49833 \times 28{,}863) + (1.79503 \times 15.313) + (1.9859 \times 5.145) + (2.045 \times 490.5) + (0.1857 \times 1.89651) + (0.8169 \times 1.71631) + (5.1058 \times 1.30468) + (6.653 \times 0.78)$

$M_{A1} = 52.361 + 74.593 + 43.246 + 27.487 + 10.217 + 1003.073 + 0.33522 + 1.4022 + 6.6614 + 5.18934$

$M_{A1} = 1224.582 Nm$

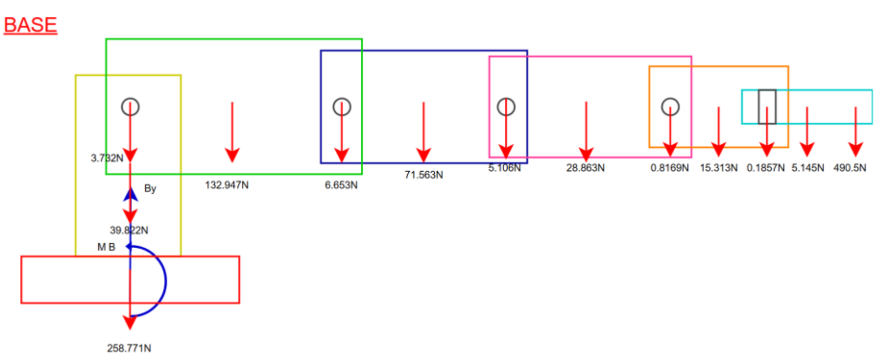


Body

$G_{By} = 760.8244 + 39.822$

$G_{By} = 800.6464N$

$M_{BB} = 1224.582Nm$, sent directly.



Base

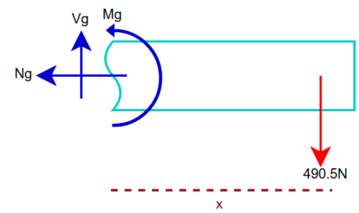
$G_{Ba} = 760.8244 + 39.822 + 258.771$

$G_{Ba} = 1059.4174N$

$M_{BB} = 1224.582Nm$, sent directly.

5.2 V-M Diagrams

Section 1



$$\sum Fx = 0$$

$$\sum Fy = 0$$

$$\sum Mg = 0$$

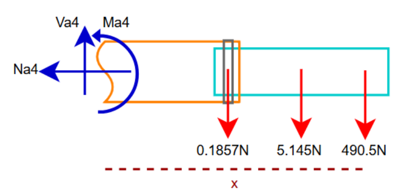
$M_g = 490.5x$

$M_g = 28.989$

$x = 2.045 - 1.9855$

$x = 0.0591$

Section 2



$x = 2.045 - 1.79503$

$x = 0.24997$

$\mathrm{V_{A4}} = 490.5 + 5.145 + 0.1857$

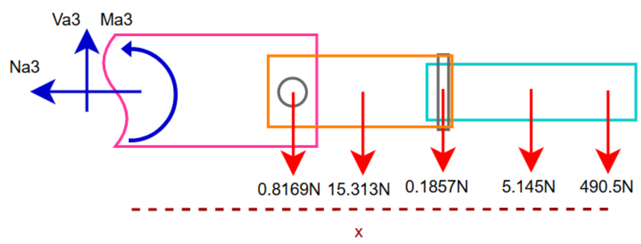
$\mathrm{V_{A4}} = 495.8357N$

$\mathrm{M_{A4}} = 490.5x + \big(5.145 \times (x - 0.591)\big) + \big(0.1857 \times (x - 0.14849)\big)$

$\mathrm{M_{A4}} = 495.8307x - 3.0683$

$\mathrm{M_{A4}} = 120.875Nm$

Section 3



$x = 2.045 - 1.4983$

$x = 0.5467$

$V_{A3} = 495.8307 + 15.313 + 0.8169$

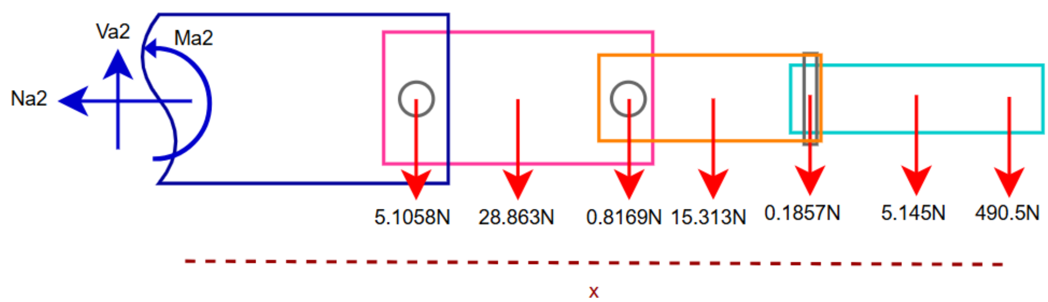
$V_{A3} = 511.9606N$

$M_{A3} = 490.5x + \left(5.145 \times (x - 0.591)\right) + (0.1857 \times (x - 0.14849)) + \left(15.313 \times (x - 0.24997)\right) + (0.8169 \times (0.3285))$

$M_{A3} = 511.9606x - 7.1644$

$M_{A3} = 272.7245Nm$

Section 4



$x = 2.045 - 1.04234$

$x = 1.00266$

$V_{A2} = 511.9606 + 28.863 + 5.1058$

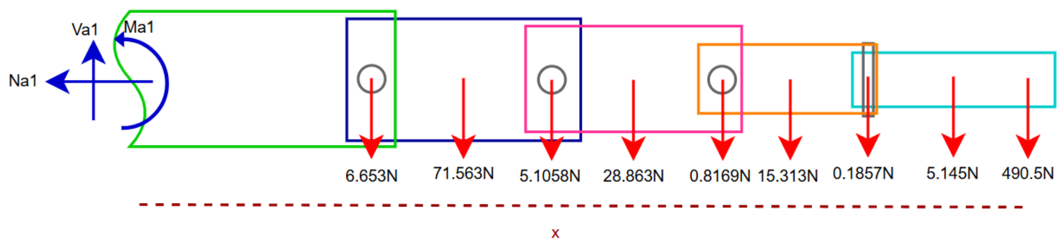
$V_{A2} = 545.9294N$

$M_{A2} = 490.5x + \left(5.145 \times (x - 0.591)\right) + \left(0.1857 \times (x - 0.14849)\right) + \left(15.313 \times (x - 0.24997)\right) + \left(0.8169 \times (x - 0.3285)\right) + \left(28.863 \times (x - 0.5467)\right) + \left(5.1058 \times (x - 0.74032)\right)$

$M_{A2} = 545.9606x - 26.7237$

$M_{A2} = 520.689Nm$

Section 5



$x = 2.045 - 0.39385$

$x = 1.65115$

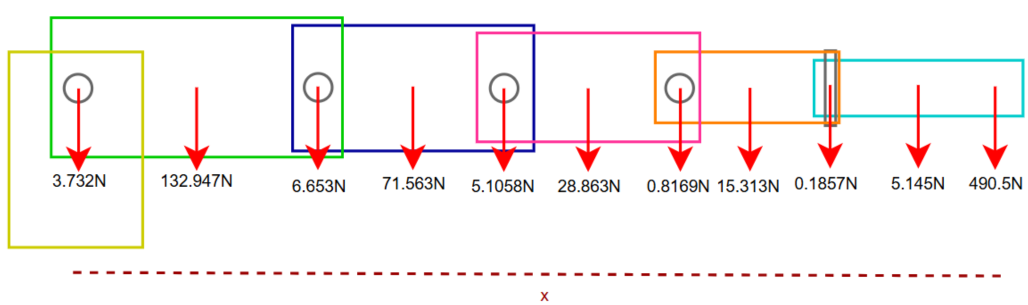
$V_{A1} = 545.9294 + 71.563 + 6.653$

$V_{A1} = 624.1454N$

$M_{A1} = 624.1454x - 106.893$

$M_{A1} = 923.666Nm$

Section 6



$x = 2.045 - 0$

$x = 2.045$

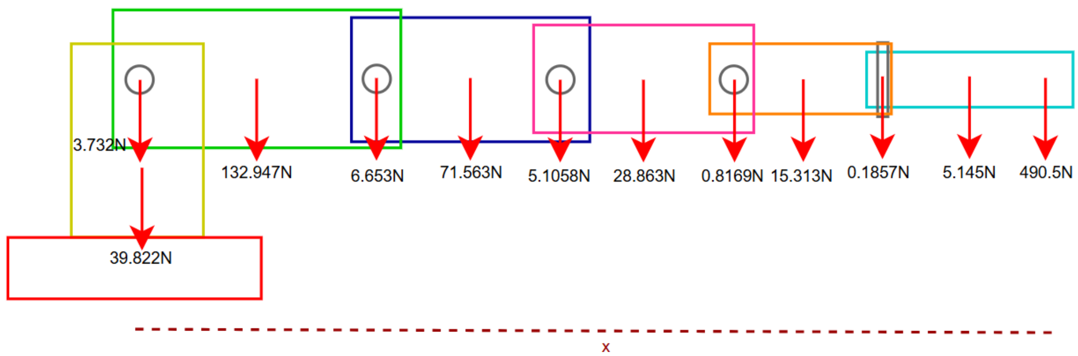
$V_{BODY} = 624.1454 + 132.947 + 3.732$

$V_{BODY} = 760.8244N$

$M_{BODY} = 757.0924x - 323.36789$

$M_{BODY} = 1224.886Nm$

Section 7

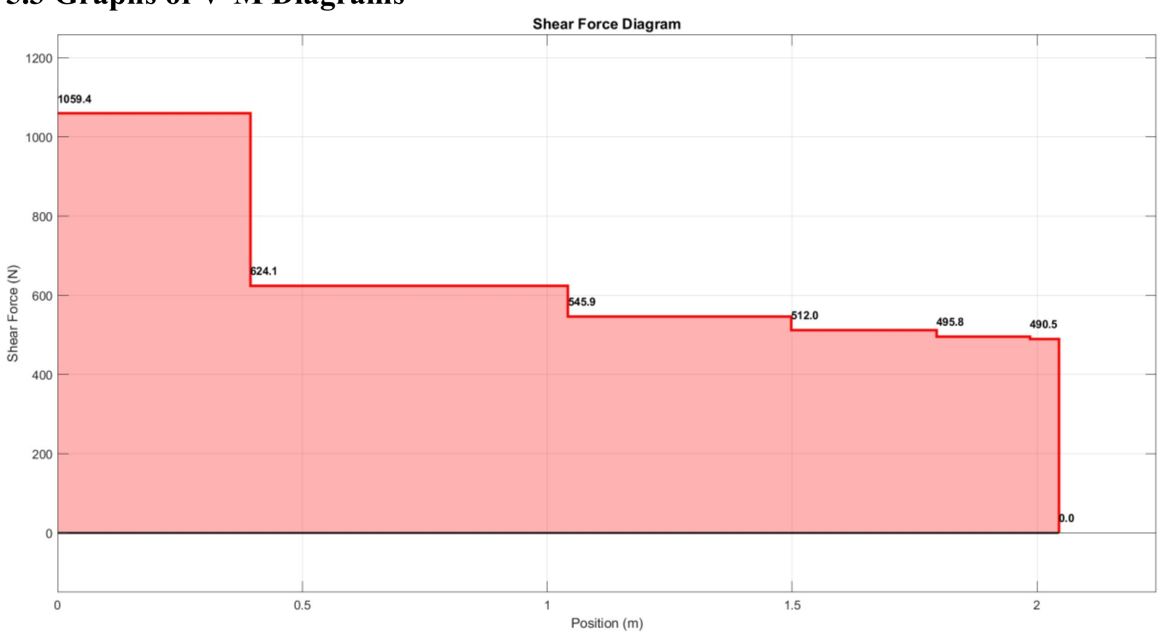


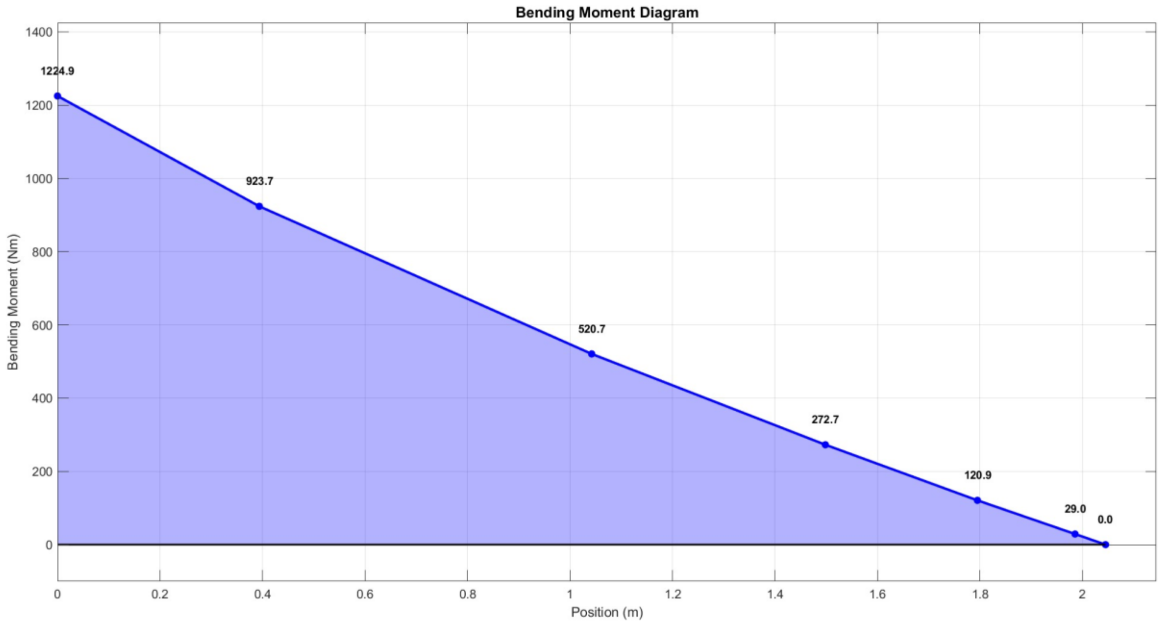
$V_{BASE} = 800.6464N$

$V_R = 1059.4174$

$M_{A1} = 1224.886Nm$

5.3 Graphs of V-M Diagrams





5.4 Bending Stress ($\sigma = M \cdot c / I$)

Gripper

$$\frac{\left((28.989 \times 0.01879)\right)}{(2 \times 0.000267)} = 1.02 \times 10^3 Pa$$

Arm4

$$\frac{(120.875 \times 0.05625)}{(0.002443)} = 2.783 \times 10^3 Pa$$

Arm3

$$\frac{(272.7245 \times 0.075)}{(2 \times 0.004006)} = 2.553 \times 10^3 Pa$$

Arm2

$$\frac{(520.689 \times 0.08625)}{(0.022451)} = 2 \times 10^3 Pa$$

Arm1

$$\frac{(923.666 \times 0.09375)}{(2 \times 0.030621)} = 1.414 \times 10^3 Pa$$

Body

$$\frac{(760.8244)}{(0.01325359)} + \frac{(1224.886 \times 0.05625)}{(0.554056)} = 5.753 \times 10^4 Pa$$

Base

$$\frac{(800.6464)}{(0.01234911)} + \frac{(1224.886 \times 0.28125)}{(0.004914)} = 1.349 \times 10^5 Pa$$

5.5 Pin Shear Stresses

Pin_3.4

$$\frac{511.9606}{2 \times 0.00070686} = 333.047 kPa$$

Pin_2.3

$$\frac{545.9296}{2 \times 0.0044186} = 61.776 kPa$$

Pin_1.2

$$\frac{624.1456}{2 \times 0.0044186} = 70.627 kPa$$

Pin_Holes

$$\frac{760.8244}{2 \times 0.00159043} = 239.188 kPa$$

Pin_Gripper

$$\frac{495.8307}{2 \times 0.00017671} = 1402.950 kPa$$

5.6 Bearing Stresses

Pin_3.4

$$\frac{511.0606}{0.03 \times 0.12375} = 137901.8451 Pa$$

Pin_2.3

$$\frac{545.9296}{0.075 \times 0.12375} = 58820.69764Pa$$

Pin_1.2

$$\frac{624.1456}{0.075 \times 0.16125} = 51608.9385Pa$$

Pin_Holes

$$\frac{760.8244}{0.075 \times 0.25125} = 40375.42421Pa$$

Pin_Gripper

$$\frac{495.8307}{0.015 \times 0.1125} = 293825.6Pa$$

5.7 Max Deflection ($\delta = P \cdot L^3 / (3 \cdot E \cdot I)$)

Gripper

$$\frac{(495.8307) \times (0.14849)^3}{(3) \times (1.07 \times 10^9) \times (0.000017)} = 2.97489 \times 10^{-5}\ Meters$$

Arm4

$$\frac{(511.9606) \times (0.18)^3}{(3) \times (1.07 \times 10^9) \times (0.000002)} = 4.65070 \times 10^{-4}\ Meters$$

Arm3

$$\frac{(545.9296) \times (0..41183)^3}{(3) \times (1.07 \times 10^9) \times (0.000016)} = 7.42447 \times 10^{-4}\ Meters$$

Arm2

$$\frac{(624.1456) \times (0.52468)^3}{(3) \times (1.07 \times 10^9) \times (0.000005)} = 5.61687 \times 10^{-3}\ Meters$$

Arm1

$$\frac{(760.8244) \times (0.78)^3}{(3) \times (1.07 \times 10^9) \times (0.000065)} = 1.73041 \times 10^{-3}$$

Body

$$\frac{(1224.886) \times (0.29505)^2}{(2) \times (1.07 \times 10^9) \times (0.000183)} = 2.72281 \times 10^{-4}$$

Gripper Total Deflection $= 8.8568 \times 10^{-3}$

Arm4 Total Deflection $= 8.8271 \times 10^{-3}$

Arm3 Total Deflection $= 8.3620 \times 10^{-3}$

Arm2 Total Deflection $= 7.6196 \times 10^{-3}$

Arm1 Total Deflection $= 2.0027 \times 10^{-3}$

Body Total Deflection $= 2.7228 \times 10^{-4}$

5.8 Buckling Calculations ($P_{cr} = \pi^2 \cdot E \cdot I / (K \cdot L)^2$)

Body

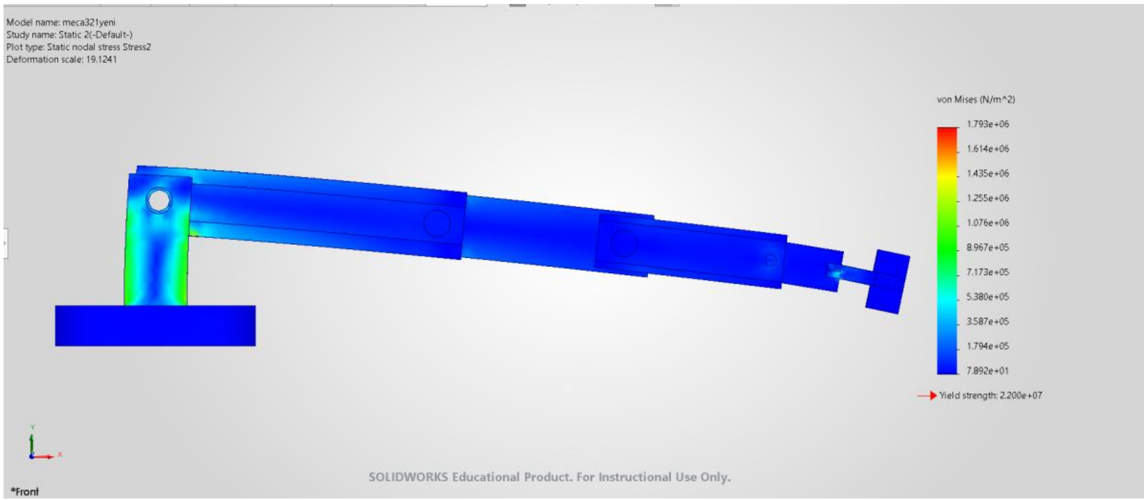
$$\frac{9.87 \times (1.07 \times 10^9) \times (0.000021)}{(2 \times 0.3651)^2} = 415.937kN$$

Cylinder

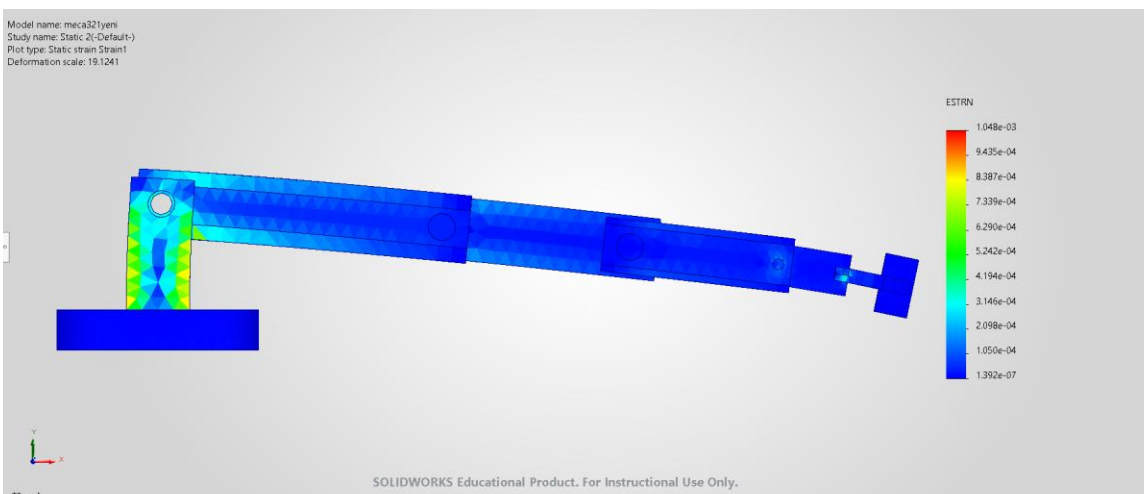
$$\frac{9.87 \times (1.07 \times 10^9) \times (0.00002)}{(1 \times 0.24375)^2} = 355.501kN$$

6. Simulation Results

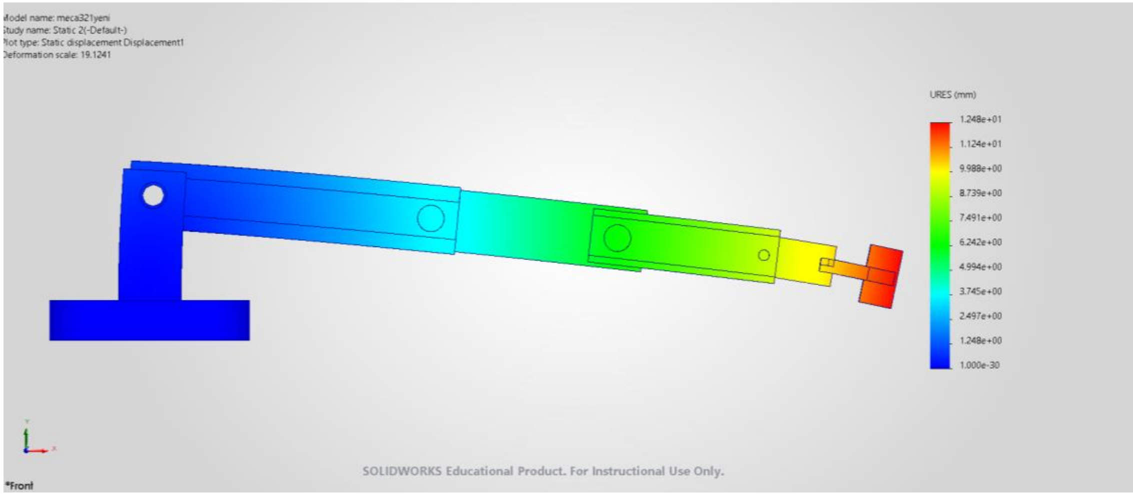
6.1 Stress Results



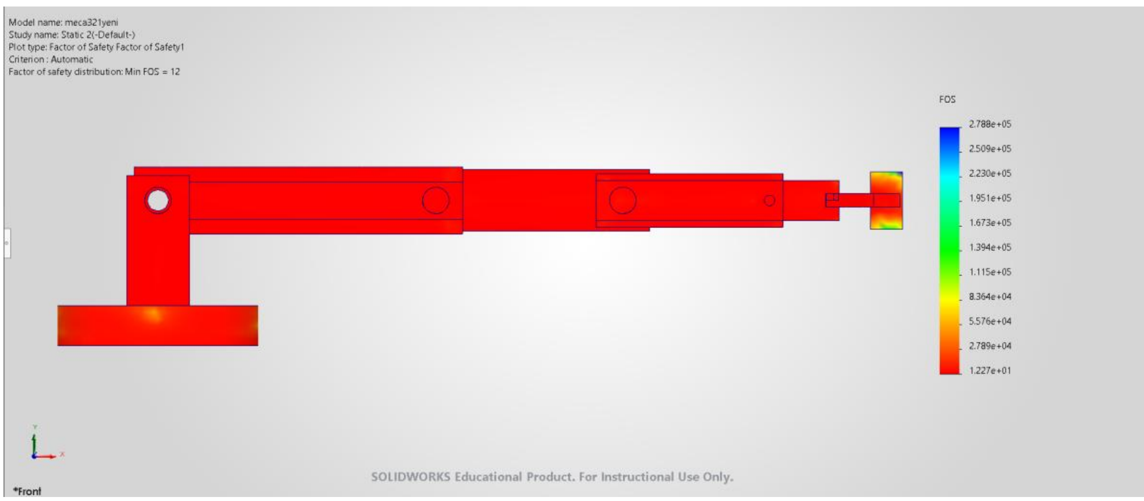
6.2 Strain Results



6.3 Displacement Results



6.4 Factor of Safety Results



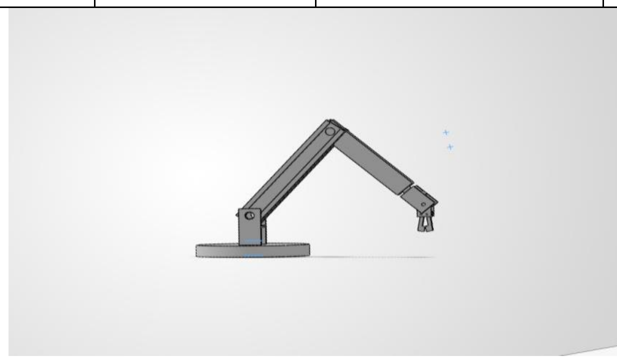
7. Design Iteration and Optimization

The design process was not linear but involved repeated cycles to satisfy the conflicting requirements of high payload capacity (50 kg) and minimum structural weight, as required by project objectives. Based on the initial analysis results, several optimizations were used to refine the robotic arm.

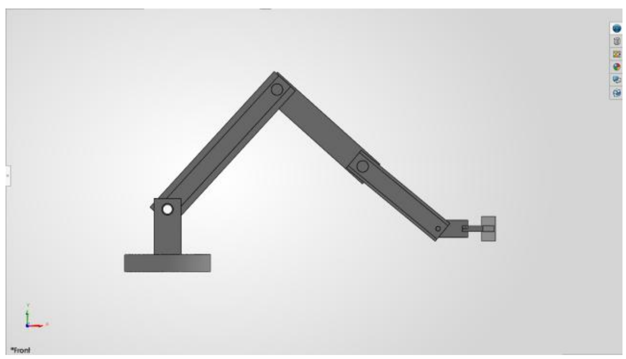
Table 2: **Structural performance comparison between initial and optimized design**

Design	Mass (kg)	Max Stress (MPa)	FOS
Initial Concept (Big and Thick Profiles)	1980	7.92	30.5

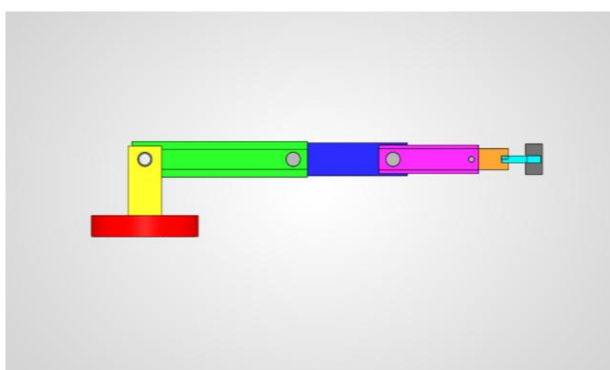
Second Concept (Long Arms)	352	1.89	15
Final Optimized Design (Tapered I-Beam)	57.2	1.79	12.3



Initial Concept (Big and Thick Profiles)



Second Concept (Long Arms)

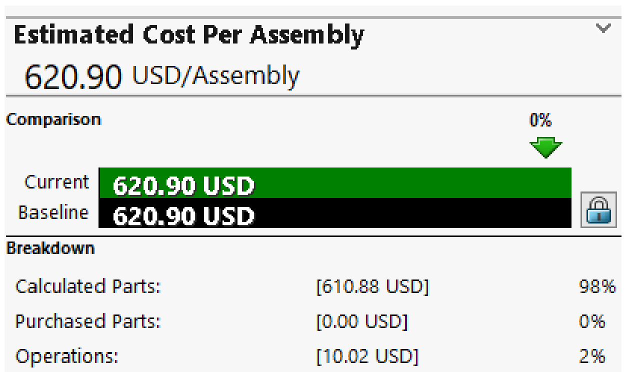


Final Optimized Design (Tapered I-Beam)

8. Cost Analysis

To evaluate the cost effectiveness of the design, an automated cost estimation was performed using the **SolidWorks Costing** module. Unlike simple raw material calculations, this analysis provides a detailed estimate that includes material costs, manufacturing operations (milling, drilling), and setup times for the HDPE components.

As shown in the SolidWorks generation report below (**Figure 7.1** and **Figure 7.2**), the total estimated manufacturing cost for the robotic arm assembly is **$ *620.90*USD**.



9. Distribution of Project Responsibilities

The specific contributions of each team member are outlined below:

- **Emir Eren:** Responsible for the design and simulation tasks. He created the 3D model in SolidWorks, ran the stress analysis tests (FEA), and prepared the motion animation video.

- **Serra Lal Tosun & Yağız Gelen:** Focused on calculations and the technical report. They checked the simulation results using manual formulas (Free Body Diagrams) and performed the cost analysis based on market prices. They also organized and wrote the final report details.

- **Selin Rabia Kinsiz:** Managed the presentation and supported the calculations. She helped the team with the mathematical verifications and summarized these analysis results to design a clear and effective presentation file.

- **Collaborative Effort:** Although everyone had specific tasks, the group worked together on every stage of the project. We brainstormed the initial design ideas, decided on the HDPE material, and solved the design problems together. Also, every group member reviewed and approved the final report and analysis results before submission.

10. Conclusions

The primary objective of this project was to design, analyze, and optimize an industrial robotic arm capable of manipulating a **50 kg payload** at a maximum reach of **2 meters**. Through a comprehensive engineering process involving geometric concept, material selection, and Finite Element Analysis (FEA), the design has been validated to meet and exceed all specified performance criteria.

The key findings and achievements of the study are summarized as follows:

- **Compliance with Safety Standards:** The structural analysis confirms that the arm is mechanically safe under the worst-case static loading scenario. The maximum Von Mises stress was recorded at 1.79 MPa, which is significantly lower than the Yield Strength of HDPE (22 MPa). Consequently, the design achieved a minimum Factor of Safety (FoS) of 12.3, higher than the project requirement of FoS > 2.

- **Geometric Optimization and Weight Efficiency**: By moving from initial solid blocks to tapered I beam profiles, the design successfully maximized the strength to weight ratio. This optimization strategy maintained the necessary rigidity while limiting the total structural mass to 57.2 kg, as a result reducing the inertial load on the base actuators.

- **Stiffness and Serviceability**: Despite the low elastic modulus of the selected polymer material (HDPE), the optimized geometry provided sufficient stiffness. The maximum deflection at the end effector was calculated as 12.48 mm. Given the significant arm span of 2 meters, this displacement is within acceptable limits for the intended material handling application.

- **Economic and Manufacturing Feasibility:** The cost estimation analysis performed via SolidWorks Costing indicates a total manufacturing cost of approximately $2,929.73 USD. This demonstrates that the proposed HDPE based design offers a cost-effective alternative to traditional metallic robotic arms without weakening structural integrity.

In conclusion, the proposed robotic arm design satisfies all design requirements regarding payload capacity, reach, safety, and cost-efficiency. The analytical results confirm that the system is structurally strong and ready for the detailed design or prototyping phase.

AI Usage Statement

AI tools were used only for grammar checking, figure formatting, and presentation structuring. Engineering analyses, and calculations were manually performed by us.

References

[1] Dassault Systemes, *SolidWorks Simulation Documentation*

[2] HDPE Material Datasheet, Typical Mechanical Properties.

[3] ***MECA 321 – Mechanics of Materials Lecture Notes***

[4] ***Beer, F. P., Mechanics of Materials, 7th ed., McGraw Hill Education, 2015.***

[5] ***Hibbeler, R. C., Mechanics of Materials, 9th ed., Prentice Hall, 2013.***