STATIC FAILURE ANALYSIS OF A 6 DEGREE OF FREEDOM ROBOTIC ARM

MECA 321 - Mechanics of Materials

İstanbul Bilgi University

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PROBLEM DEFINITION

- *Payload: 50 kg*
- *Maximum reach: 2 m*
- *Static lifting condition*
- *Structural safety requirement*

PROJECT OBJECTIVES

- *Safe operation (FoS ≥ 2)*
- *Weight optimization*
- *Manufacturable geometry*
- *Cost awareness*

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DESIGN REQUIREMENTS

- *Static loading*
- *Fully extended worst-case position*
- *Industrial profiles (I-beams)*
- *Pin-connected joints*

MODELING ASSUMPTIONS

- *Linear elastic behavior*
- *HDPE isotropic material*
- *Fixed base*
- *No dynamic or thermal effects*
- *Bending dominated loading; axial, torsional and buckling effects are negligible under static worst case pose.*

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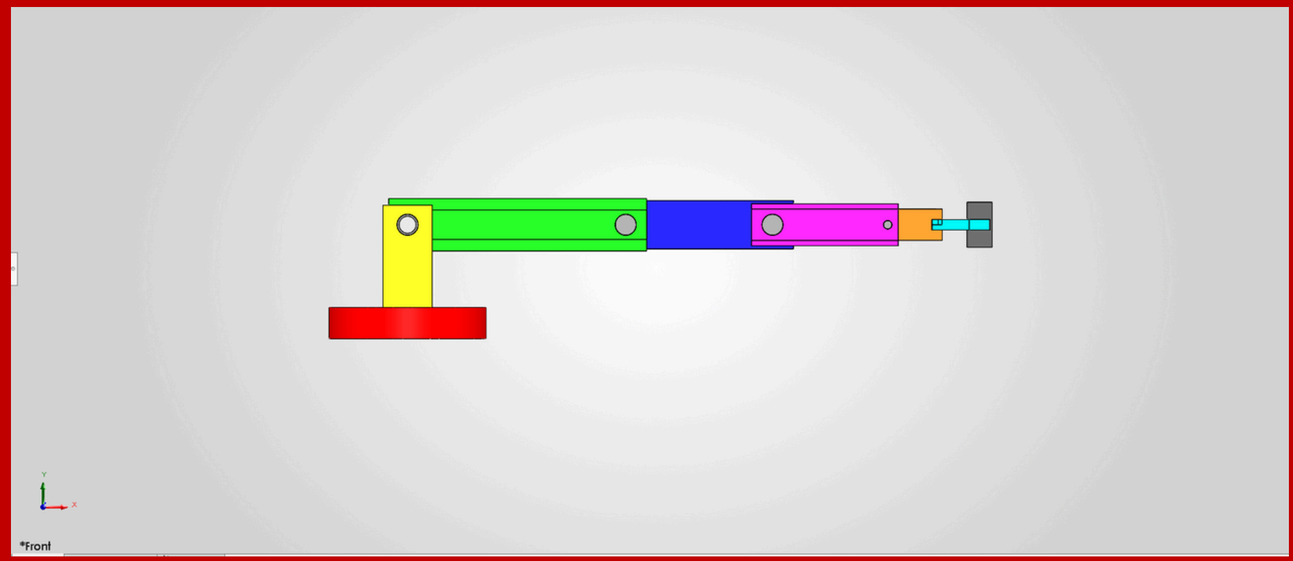
CONCEPTUAL DESIGN

- *Serial robotic arm*
- *Step-down geometry*
- *Load transferred to base*



CAD Design of the Robotic Arm

6 DOF MOTION ANIMATION

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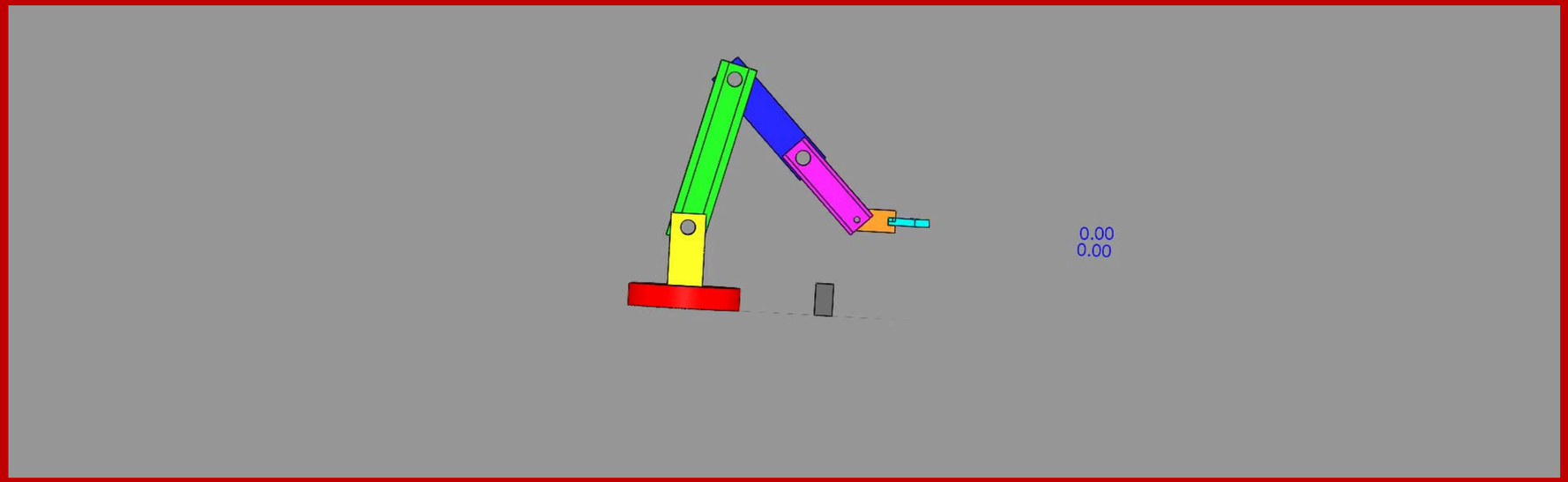

Motion animation illustrating the six degrees of freedom of the robotic arm. The fully extended configuration corresponds to the worst-case loading condition used in static analysis.

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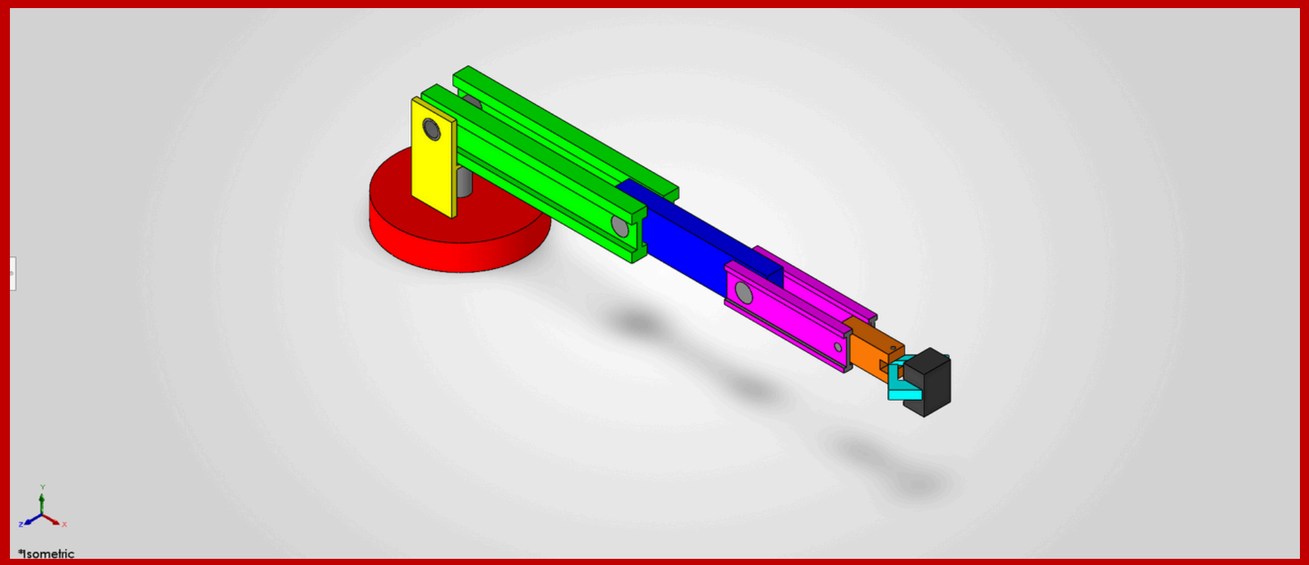
CONFIGURATION & DOF

- *Revolute joints*
- *Serial linkage*

- *6 DOF serial manipulator. Static analysis performed at a fully extended worst case pose.*



Revolute joint based serial configuration

MATERIAL SELECTION

- *Material: HDPE*
- *Low density*
- *Cost-effective*
- *Sufficient strength*
- *$E = 1.07$ GPa, $\sigma_y = 22$ MPa, $\rho = 960$ kg/m³*

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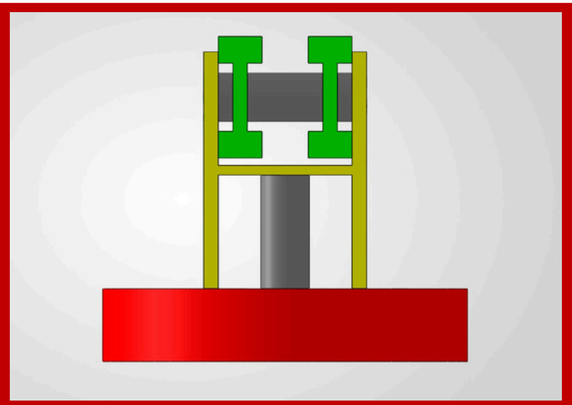
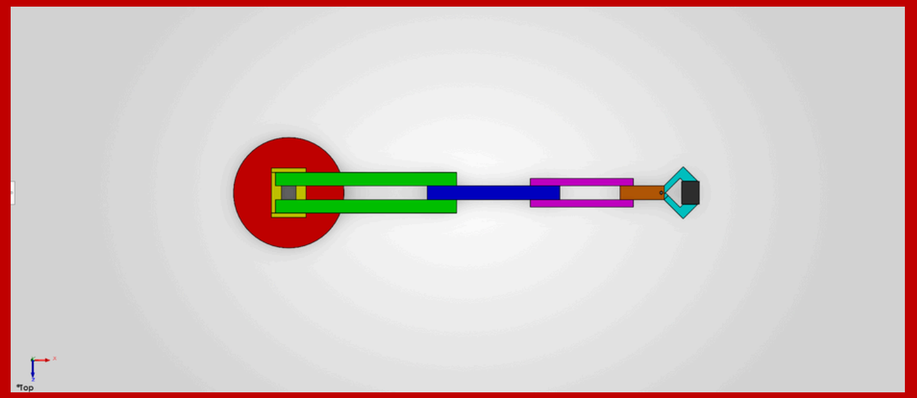
CROSS SECTION SELECTION

- *Industrial I-beam profile*
- *High moment of inertia*
- *Bending resistance*
- *Bending-dominated loading*
- *Section modulus selected to satisfy FoS ≥ 2*



I-beam cross-section used to increase bending stiffness



Complete SolidWorks assembly of the robotic arm

CAD MODEL

- *Individual part modeling*
- *Assembly with pin joints*
- *Worst-case configuration*

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MASS DISTRIBUTION AND CENTER OF MASS

- *Progressive mass reduction*
- *Payload dominates loading*
- *Reduced base moment*
- *Total structural mass = 57.2 kg*

	Center of Mass			Mass	Force
	X	Y	Z	kg	Newton
BASE	0	0.056	0	26.3783	258.771123
BODY	0	0.28805	0	3.03418	29.7653058
ARM_1	0.39385	0.40755	0	13.55224	132.9474744
ARM_2	1.04234	0.40755	0	7.29488	71.5627728
ARM_3	1.49833	0.40755	0	2.9422	28.862982
ARM_4	1.79503	0.40755	0	1.561	15.31341
GRIPPER	1.9859	0.40755	0	0.52451	5.1454431
LOAD	2.045	0.40755	0	50	490.5
CYLINDER	0	0.178.13		1.02517	10.0569177
PIM_HOLE	0	0.40755	0	0.38042	3.7319202
PIM_1.2	0.78	0.40755	0	0.67819	6.6530439
PIM_2.3	1.30468	0.40755	0	0.52047	5.1058107
PIM_3.4	1.71651	0.40755	0	0.08327	0.8168787
PIM_GRIPPER	1.89651	0.40755	0	0.01893	0.1857033

Mass distribution of arm components and payload used for center of mass calculation.

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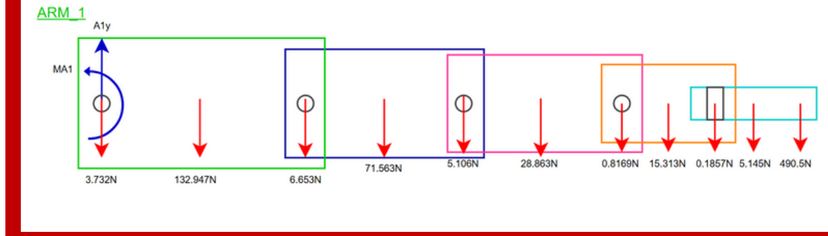
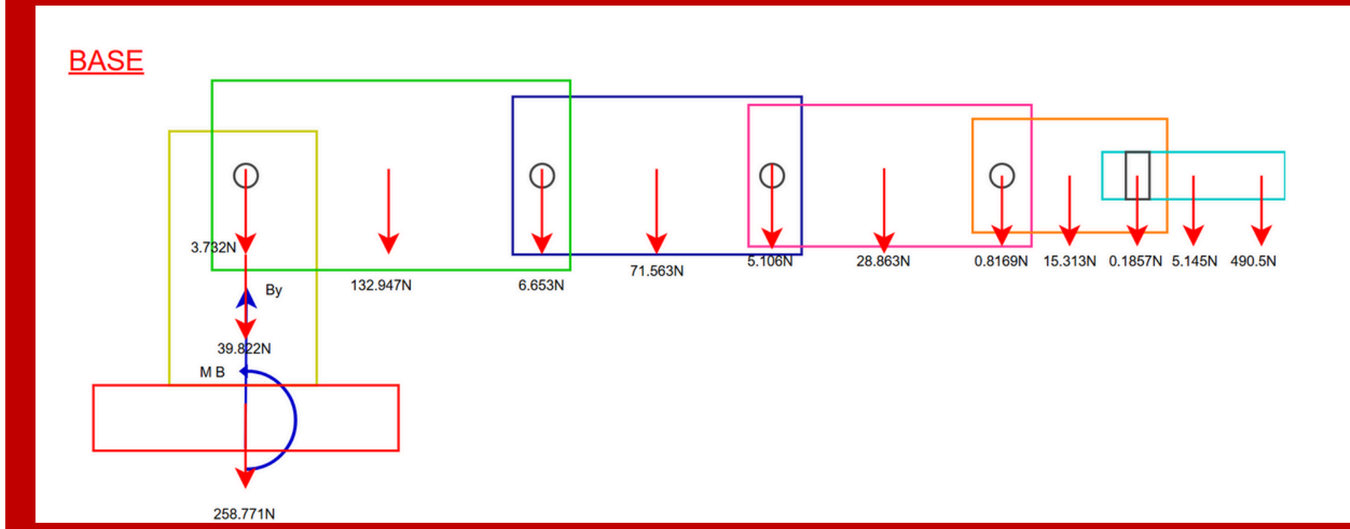
FREE BODY DIAGRAM

- *Payload and self-weight considered*
- *Base assumed fixed*



Free body diagram of an individual arm segment



Free body diagram of the complete robotic arm.

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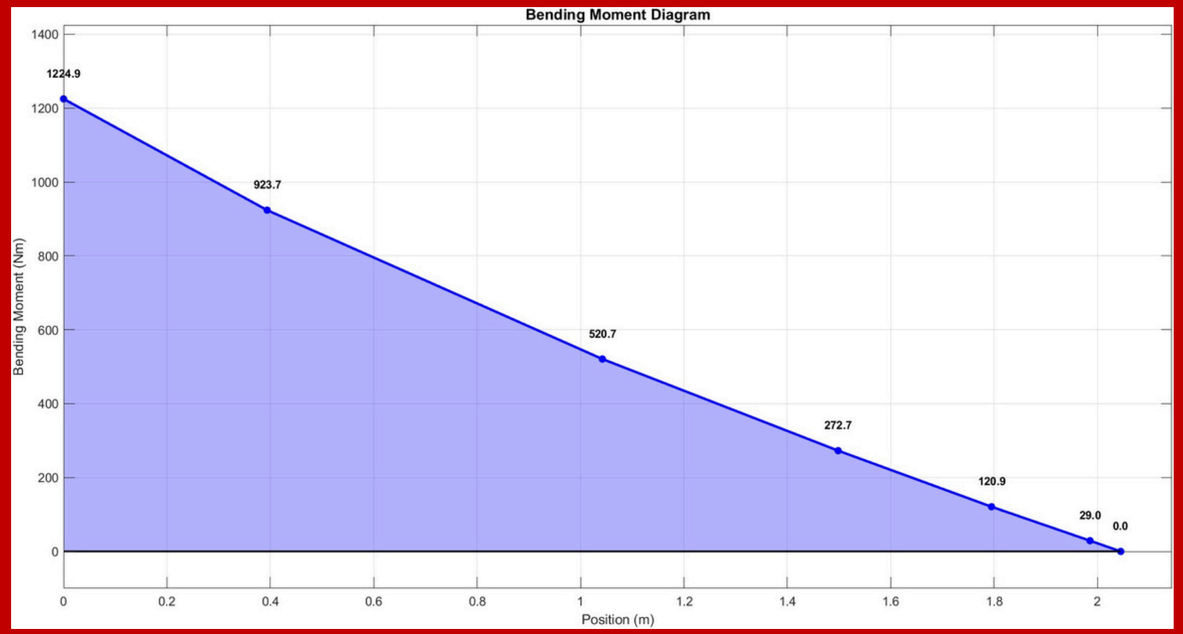
BENDING MOMENT DISTRIBUTION

- *Maximum moment at base*
- *M_max ≈ 1224.9 N·m (base)*
- *Linear decrease along arm*



Bending moment distribution along the arm under worst case loading

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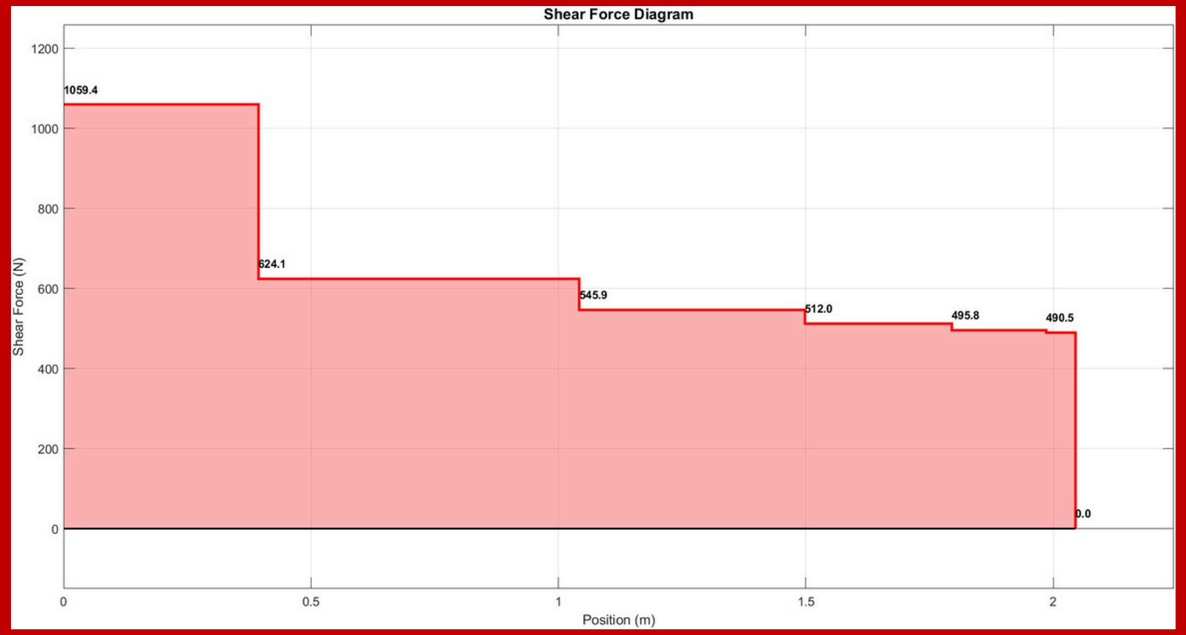
SHEAR FORCE DISTRIBUTION

- *Stepwise behavior*
- *V_max ≈ 1059.4 N (base)*
- *Discrete masses effect*



Shear force distribution caused by link weights and payload.

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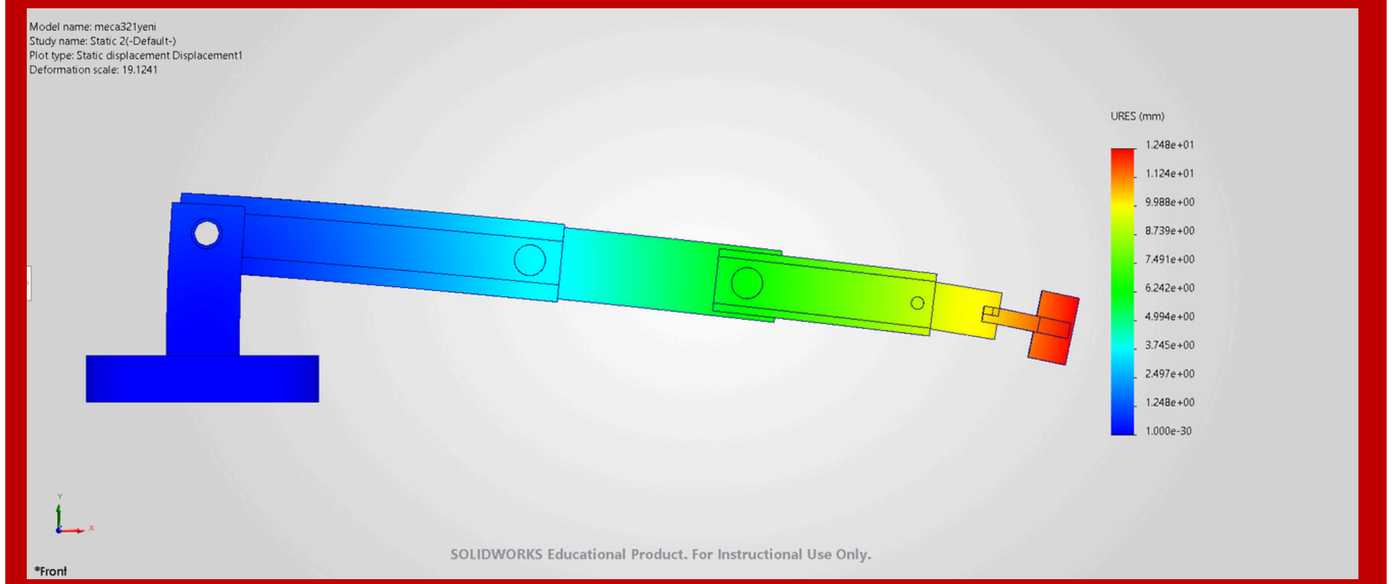
STATIC DISPLACEMENT RESULTS

- *Max displacement: 12.48 mm*
- *Relative Deflection*

  ≈ 12.48/2000 = 0.62%
- *Occurs at end-effector*



Static displacement distribution of the robotic arm under worst-case loading.

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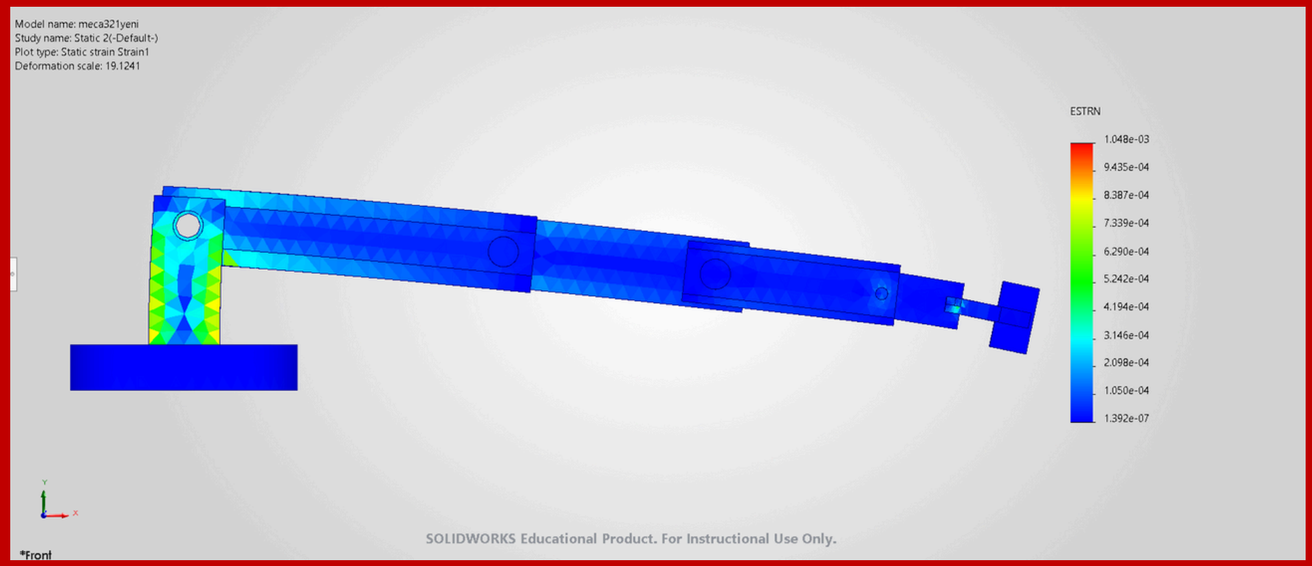
STRAIN DISTRIBUTION

- *Elastic behavior*
- *No localization*



Static strain distribution of the robotic arm under worst case loading.

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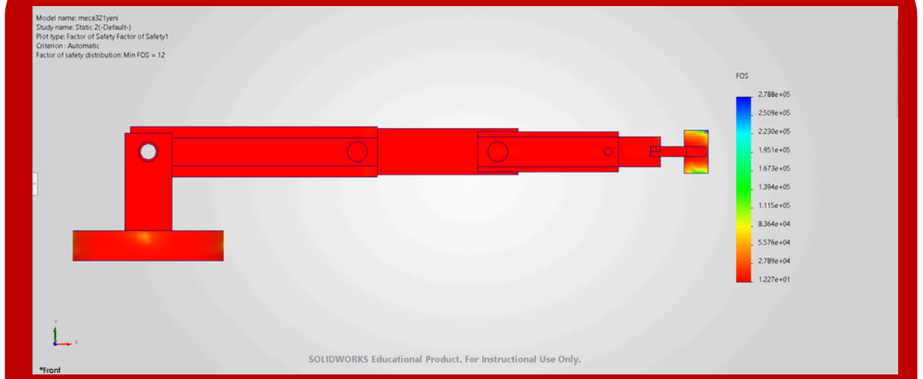
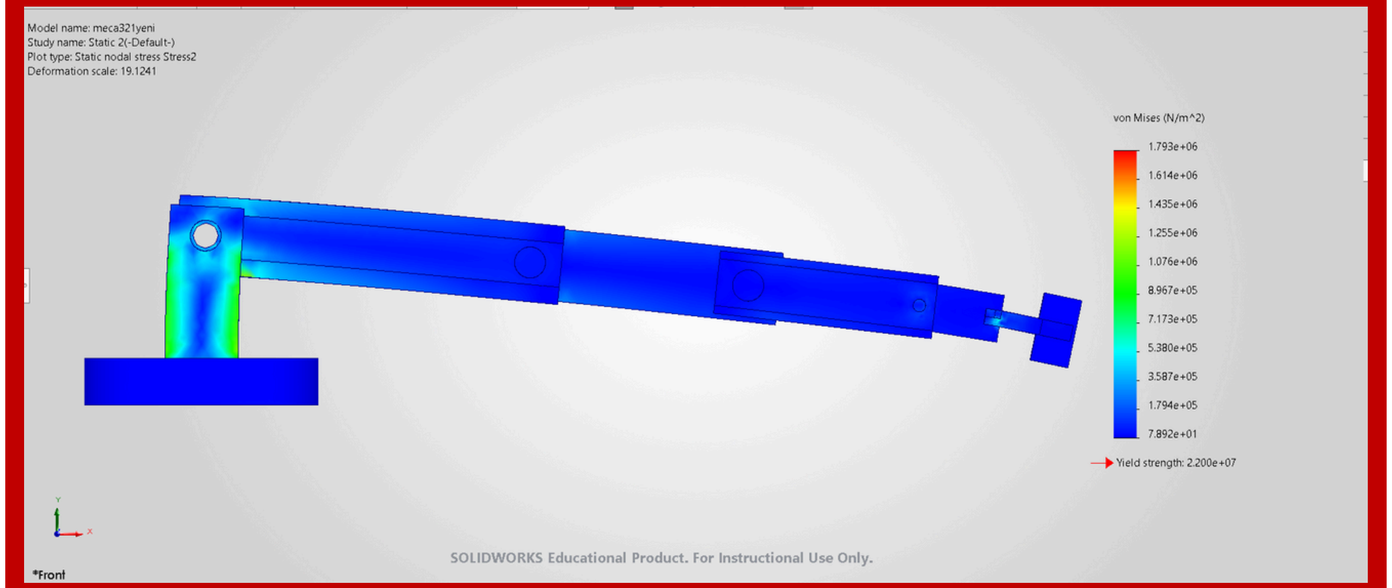
STRESS ANALYSIS

- *Max stress: 1.79 MPa*
- *Yield: 22 MPa*
- *FoS: 12.3*



Factor of safety distribution derived from stress results.

- *σ_max = 1.79 MPa, σ_y = 22 MPa → FoS ≈ 12.3*



Stress distribution under static loading.

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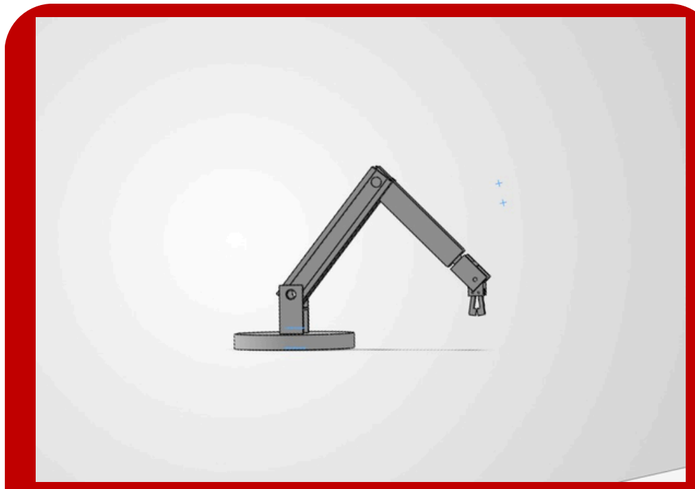
DESIGN OPTIMIZATION

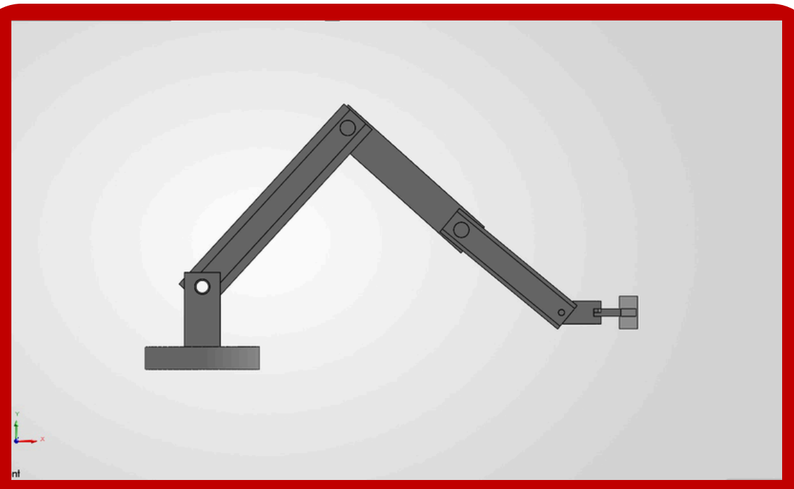
- *Design was improved step by step using stress and displacement results*
- *Cross-section and geometry were changed to reduce the total mass*
- *Material was removed from low stress regions*

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

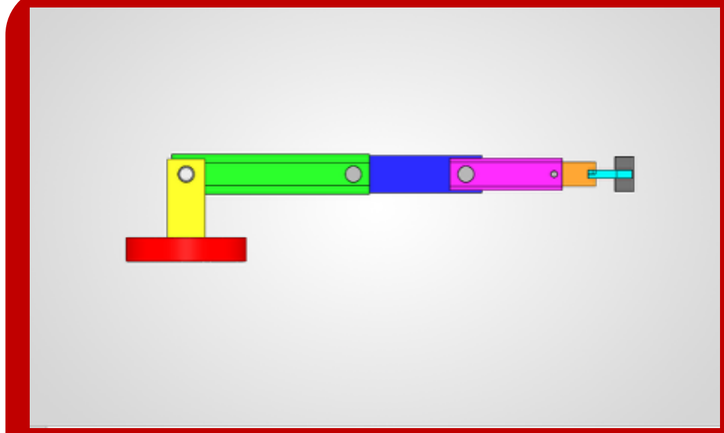
Comparison of mass, maximum stress, and factor of safety for different design iterations.



Initial Concept (Big and Thick Profiles)



Second Concept (Long Arms)



Final Optimized Design (Tapered I-Beam)

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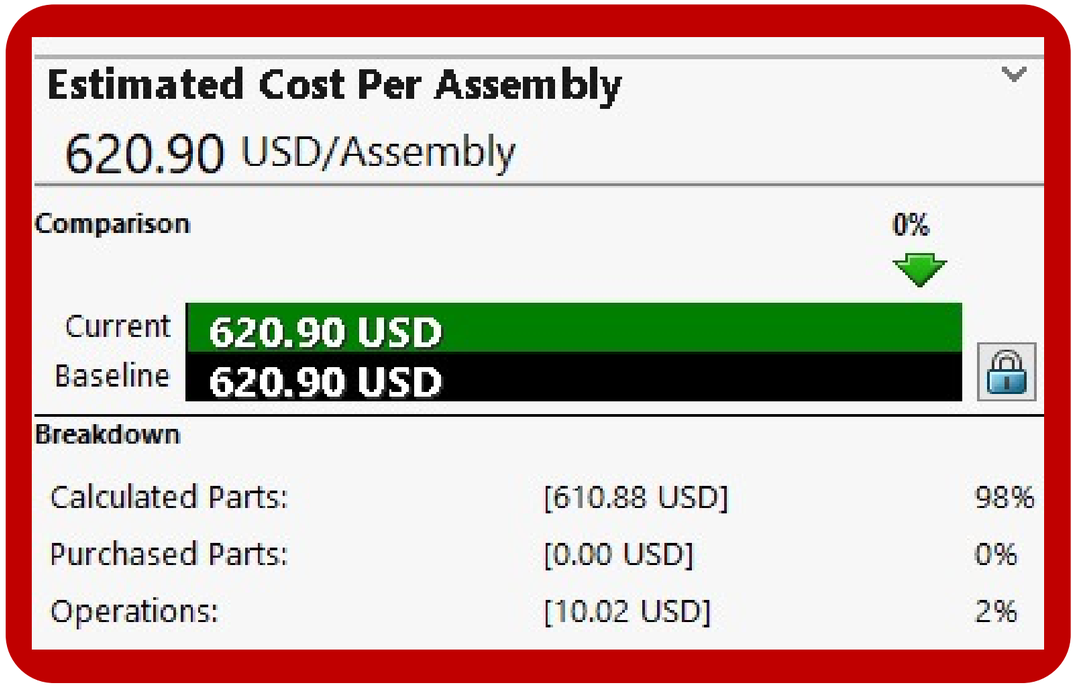
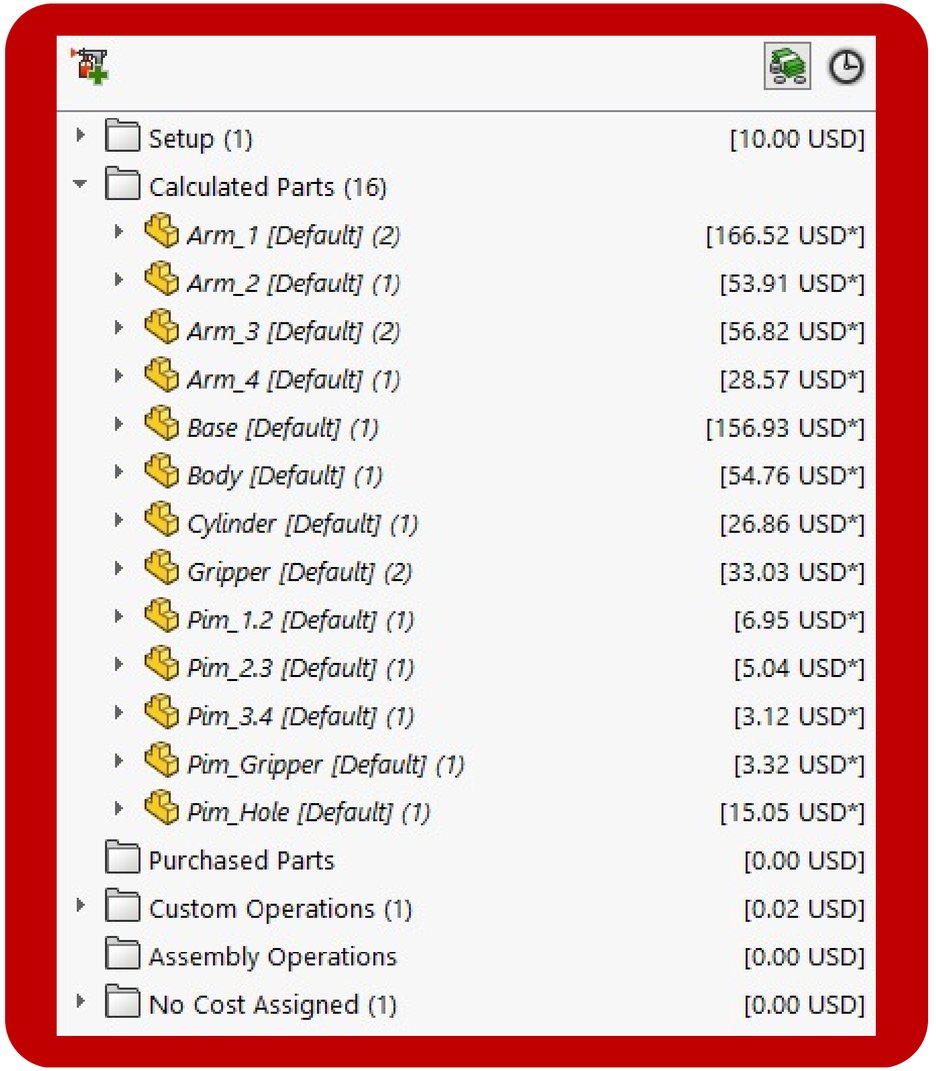
COST ANALYSIS

- *Total cost: $620.90*





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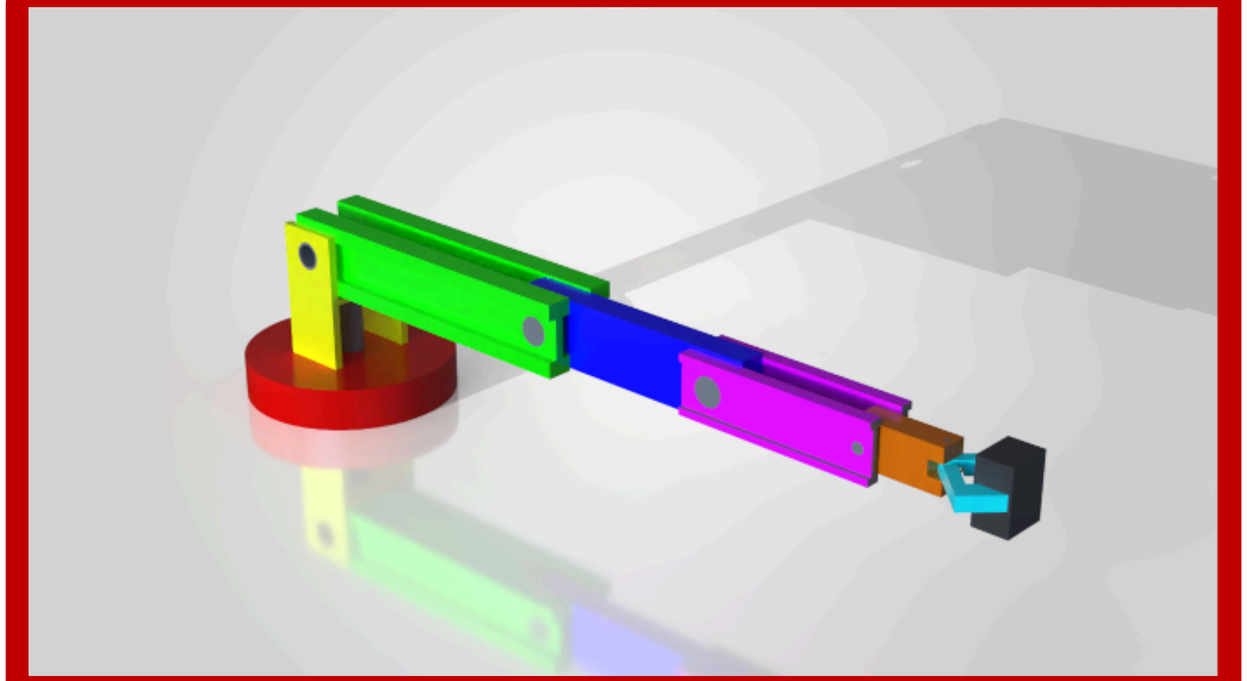
CONCLUSIONS

- *50 kg payload safely supported at 2 m reach*
- *Maximum von Mises stress: 1.79 MPa*
- *Minimum factor of safety: ≈ 12.3*
- *Maximum displacement: 12.48 mm at end effector*
- *All pins and joints satisfy shear and bearing stress limits with FoS > 2.*
- *Optimized I beam design reduced total mass to 57.2 kg*



Final optimized robotic arm design used in the static analysis.

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REFERENCES

- *SolidWorks Simulation Documentation*
- *HDPE Material Datasheet*
- *MECA 321 – Mechanics of Materials Lecture Notes*
- *Beer, F. P., Mechanics of Materials, 7th ed., McGraw Hill Education, 2015.*
- *Hibbeler, R. C., Mechanics of Materials, 9th ed., Prentice Hall, 2013.*