DESIGN AND DEVELOPMENT OF A MOBILE MANIPULATOR FOR LOGISTICS AND WAREHOUSING

ME3261: MECHATRONIC SYSTEM DESIGN PROJECT

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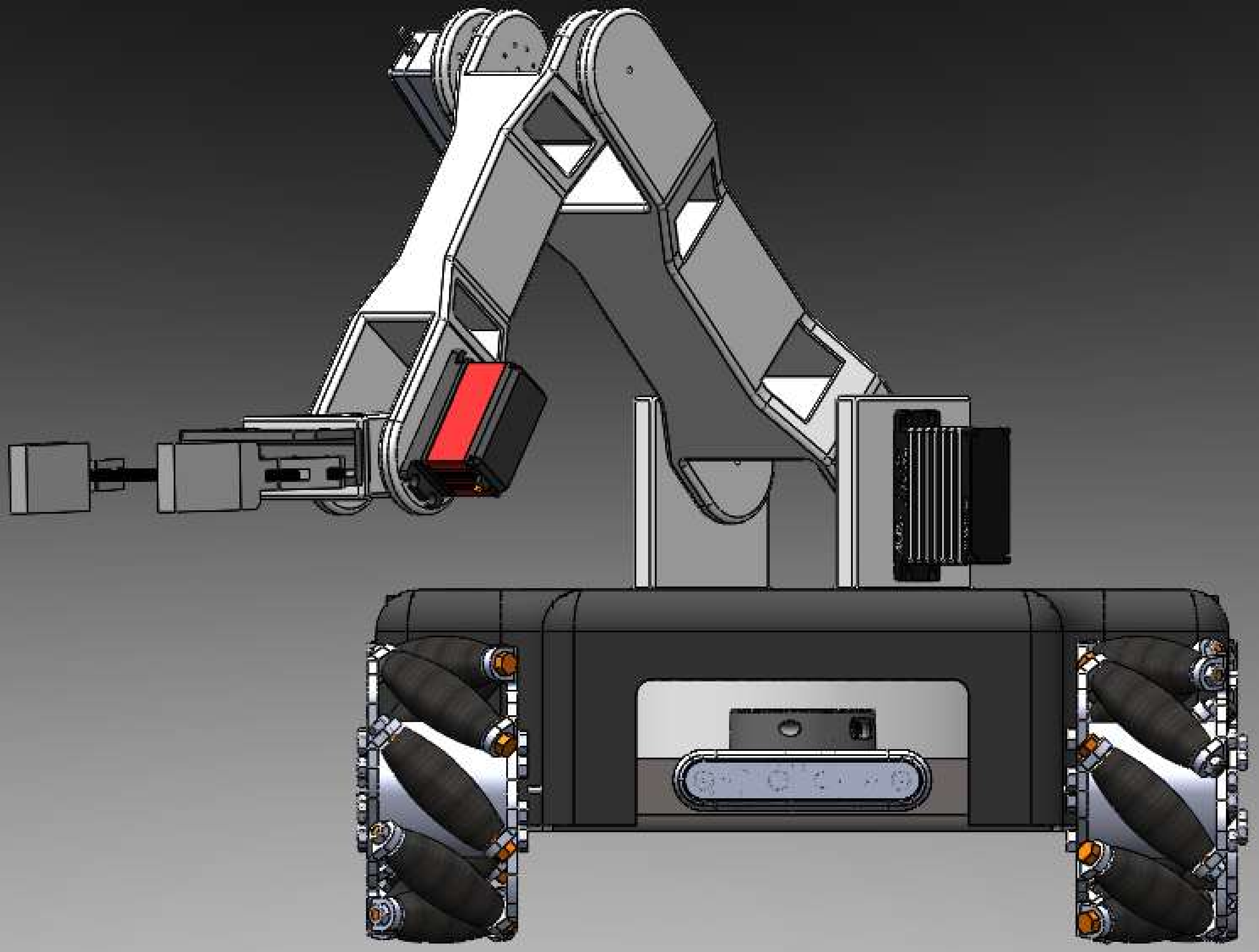
INDEX: 200102T

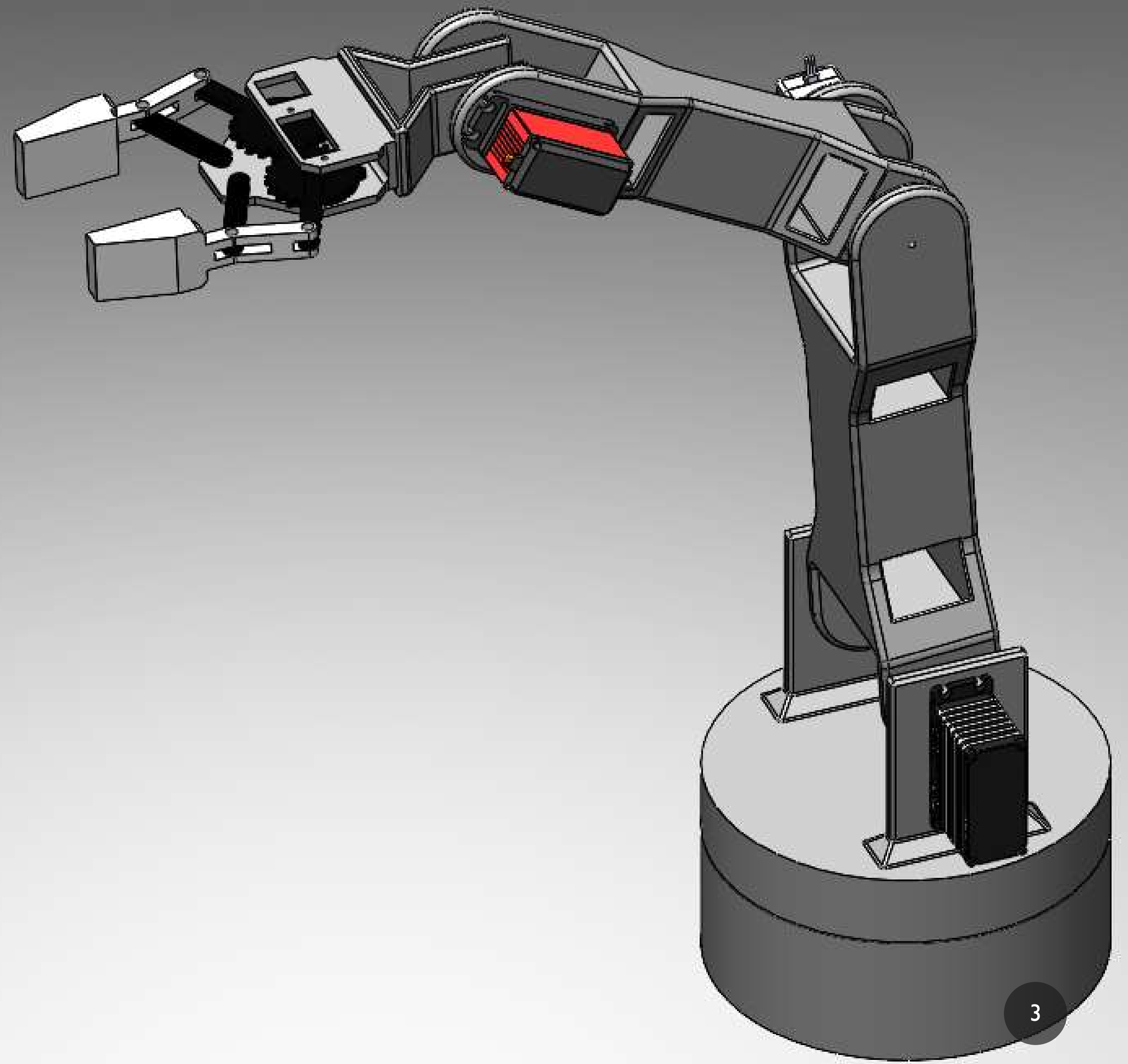
PROPOSED SYSTEM

- Main Components,
  - Mobile Base
  - Robotic Arm
  - Gripper
  - Sensor Units
  - User Interface

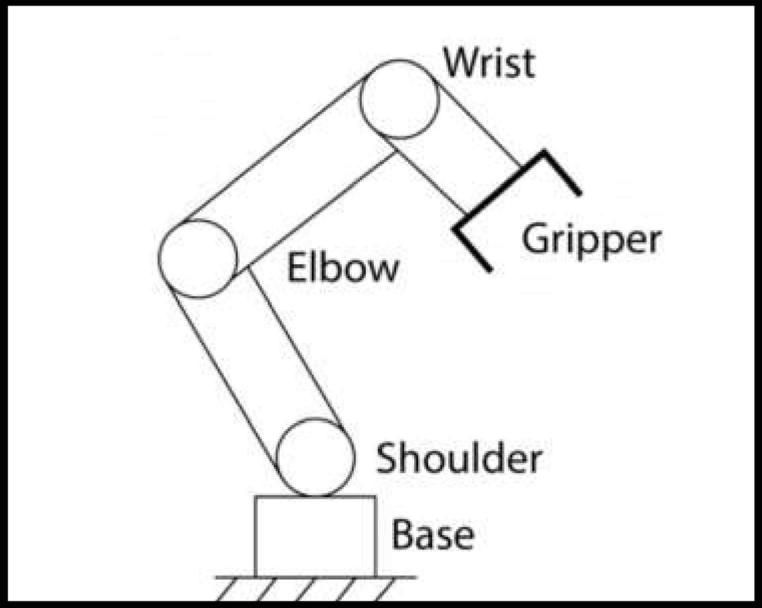


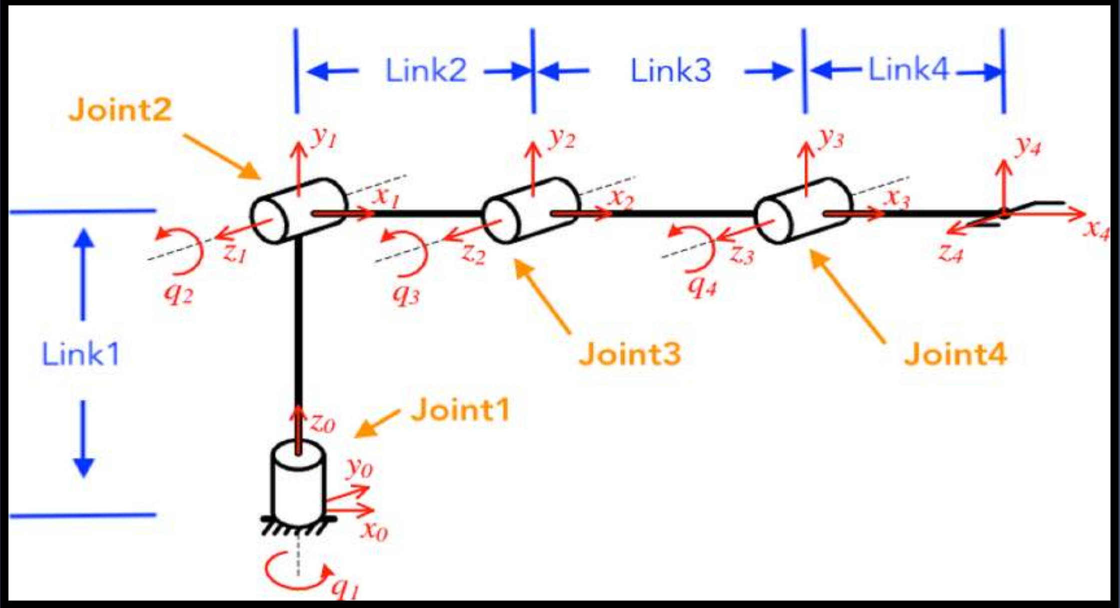
DESIGN PARAMETERS FOR THE ROBOT ARM

- Work Envelope = $0.5m^3$
- Maximum Reach = 50cm
- Payload = 2kg
- Package Size to Grip = 8×8×8 cm
- Degrees of Freedom = 4



KINEMATICS OF 4 AXIS ROBOT ARM





$\theta_1 = Base\ rotation\ (Joint\ 1)$
$\theta_2 = Shoulder\ rotation\ (Joint\ 2)$
$\theta_3 = Elbow\ rotation\ (Joint\ 3)$
$\theta_4 = Wrist\ rotation\ (Joint\ 4)$

$L_1 = Length\ from\ base\ to\ shoulder\ (Link\ 1)$
$L_2 = Length\ from\ shoulder\ to\ elbow\ (Link\ 2)$
$L_3 = Length\ from\ elbow\ to\ wrist\ (Link\ 3)$
$L_4 = Length\ from\ wrist\ to\ end\ effector\ (Link\ 4)$

KINEMATICS OF 4 AXIS ROBOT ARM CONTD.

Joint	θ_i	d_i	a_i	α_i
Base	θ_1	d_1	a_1	α_1
Shoulder	θ_2	d_2	a_2	α_2
Elbow	θ_3	d_3	a_3	α_3
Wrist	θ_4	d_4	a_4	α_4

$\theta_i = Joint\ angel$
$d_i = offset\ along\ the\ previous\ z\ axis$
$a_i = Link\ Length$
$\alpha_i = Angle\ between\ z\ axes$

FORWARD KINEMATICS OF 4 AXIS ROBOT ARM

$$Transformation\ Matrices:$$

$$T_i = \begin{pmatrix} \cos(\theta_i) & -\sin(\theta_i)\cos(\alpha_i) & \sin(\theta_i)\sin(\alpha_i) & a_i\cos(\alpha_i) \\ \sin(\theta_i) & -\cos(\theta_i)\cos(\alpha_i) & -\cos(\theta_i)\cos(\alpha_i) & a_i\text{sine}(\theta_i) \\ 0 & sin(\alpha_i) & \cos(\alpha_i) & d_i \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$Overall\ Transformation\ Matrix:$$

$$T = T_1.T_2.T_3.T_4$$

$$Final\ Forward\ Kinematics\ Equation:$$

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix} = (T_1.T_2.T_3.T_4)\begin{pmatrix} 0 \\ 0 \\ 0 \\ 1 \end{pmatrix}$$

INVERSE KINEMATICS OF 4 AXIS ROBOT ARM

$End\ effector\ position = (x, y, z)$

$\theta_1 = atan2(y, x)$

$\theta_2 = atan2(z - d_0, r) + \mathrm{acos}(\frac{L_2^2 + L^2 - L_3^2}{2L_2 L})$

$\theta_3 = \mathrm{acos}(\frac{L_2^2 + L_3^2 - L^2}{2L_2 L_3})$

$\theta_1 = \emptyset - (\theta_1 + \theta_2)$

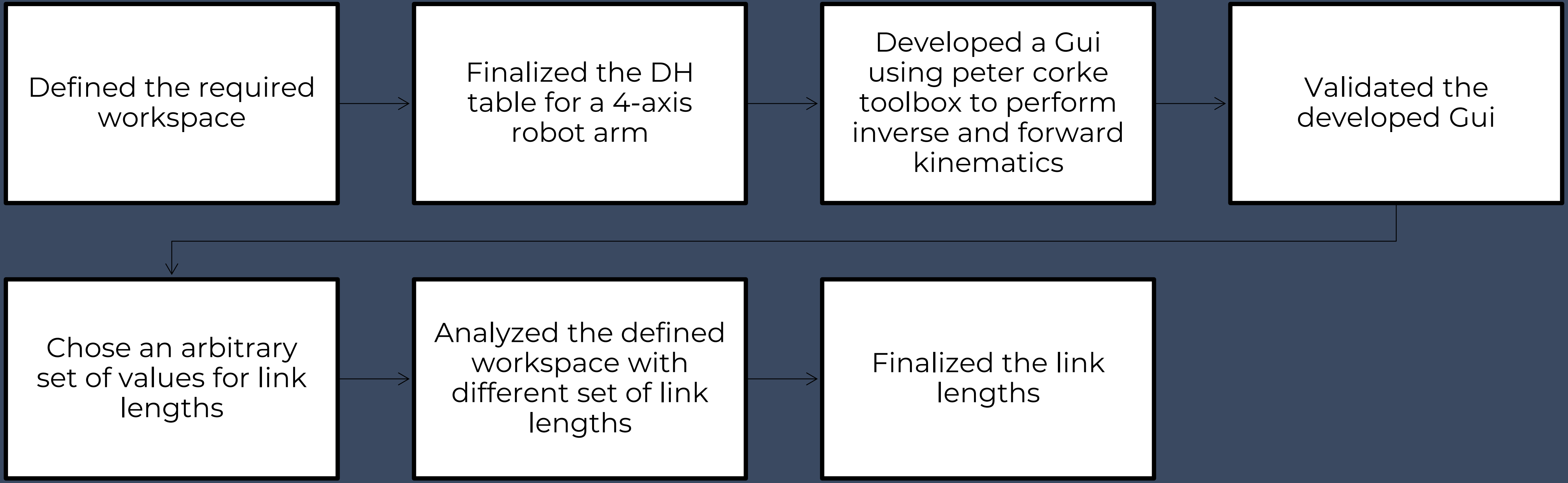
$Where:$

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

$L = \sqrt{r^2 + (z - d_0)^2}$

$\emptyset = Desired\ orientation$

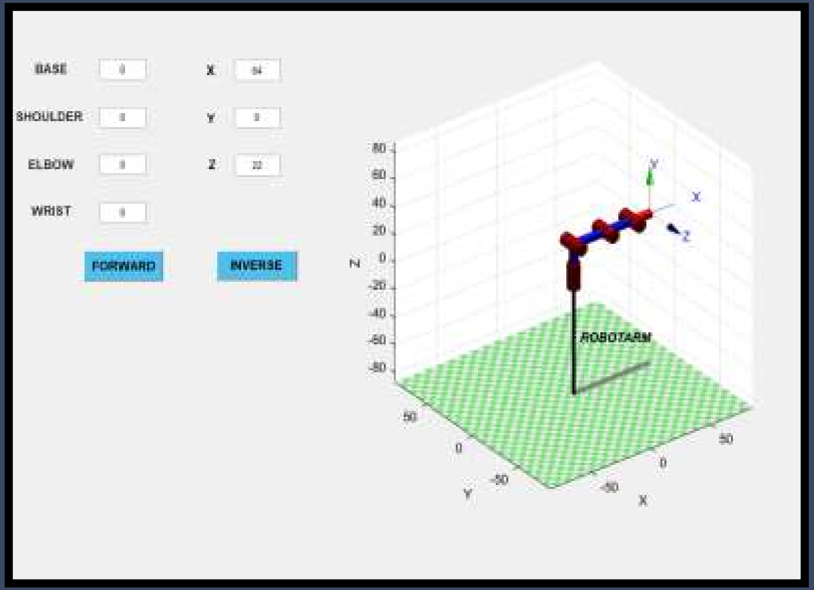
ROBOT ARM LINK LENGTH SELECTION

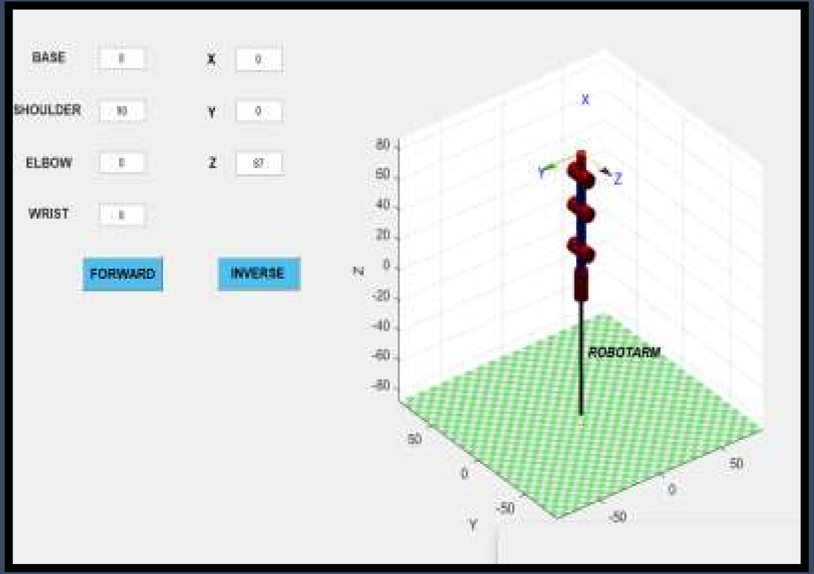


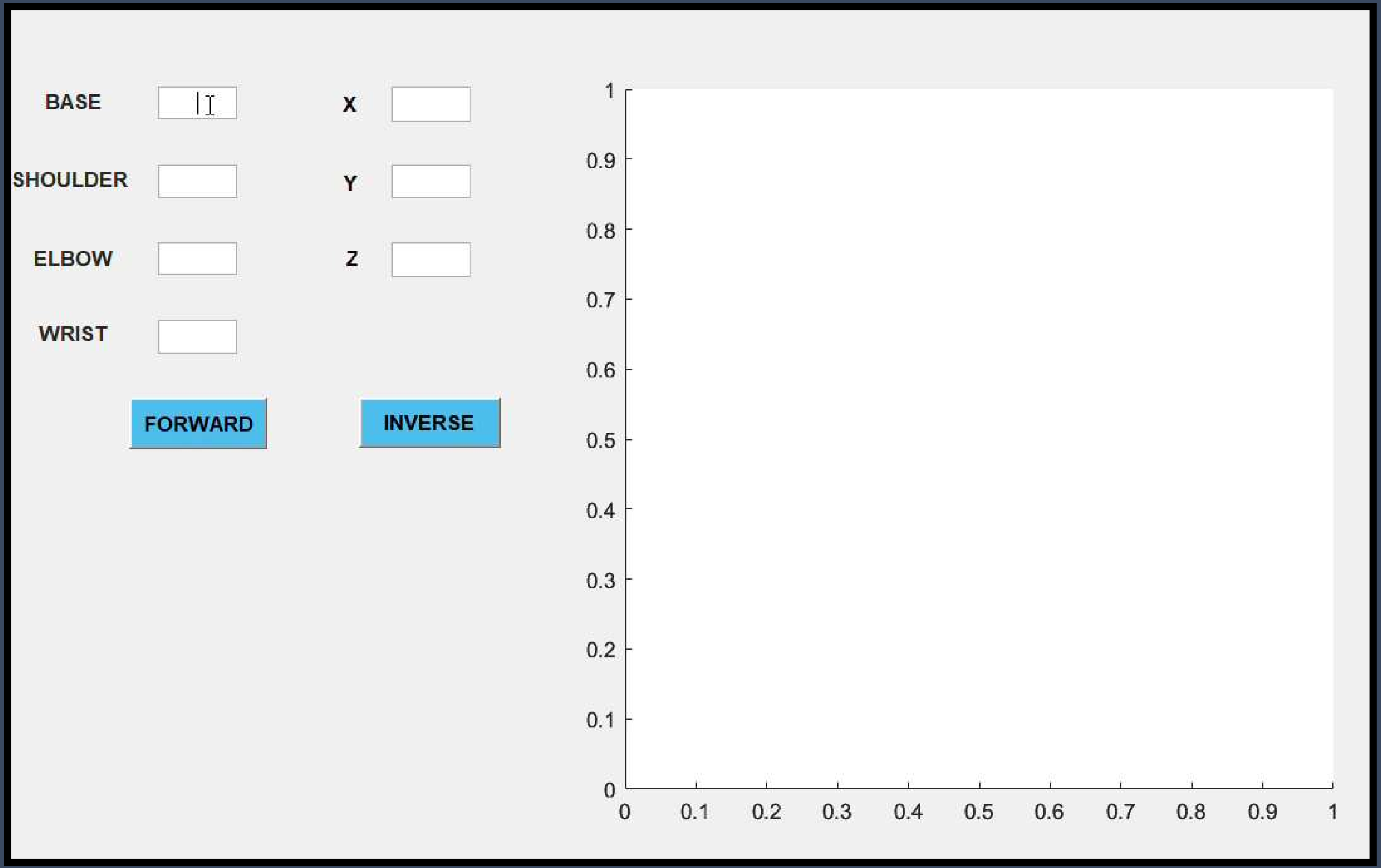
INITIAL DH PARAMETER TABLE

Joint	θ_i	d_i	a_i	α_i
Base	θ_1	L_1	0	90
Shoulder	θ_2	0	L_2	0
Elbow	θ_3	0	L_3	0
Wrist	θ_4	0	L_4	0

MATLAB GUI AND VALIDATION

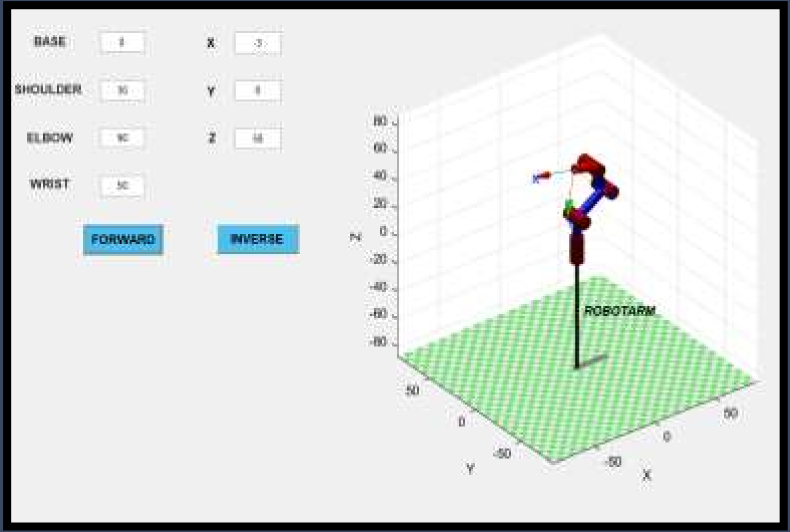


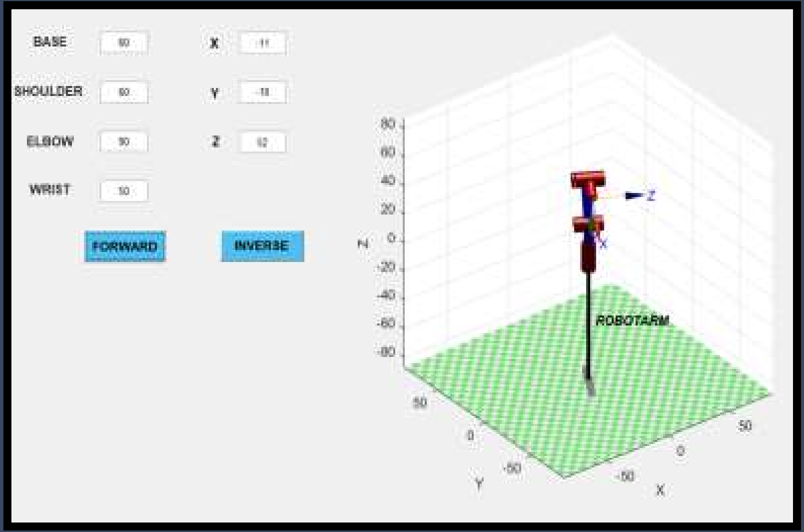


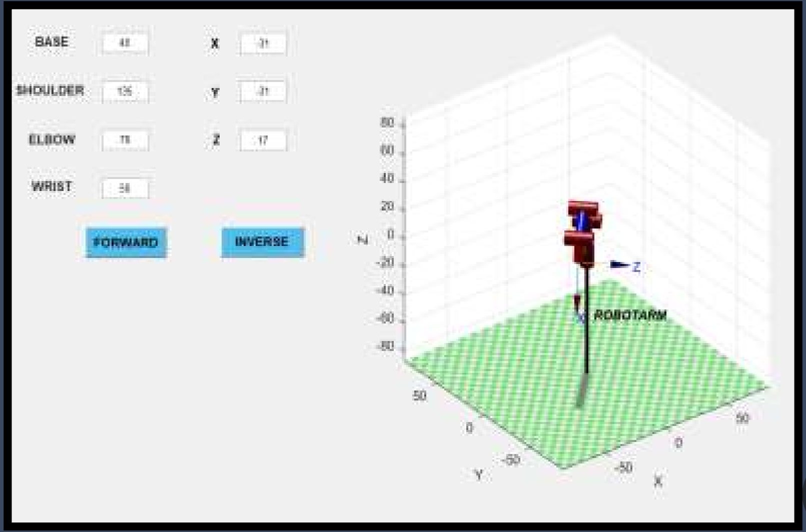


SIMULATION TEST RESULT OF FORWARD KINEMATICS

Input Angle (degree)				Output Coordinate (cm)		
θ_1	θ_2	θ_3	θ_4	X	Y	Z
0	30	90	50	-3	0	58
60	60	90	50	-11	-18	52
45	135	70	50	-31	-31	17

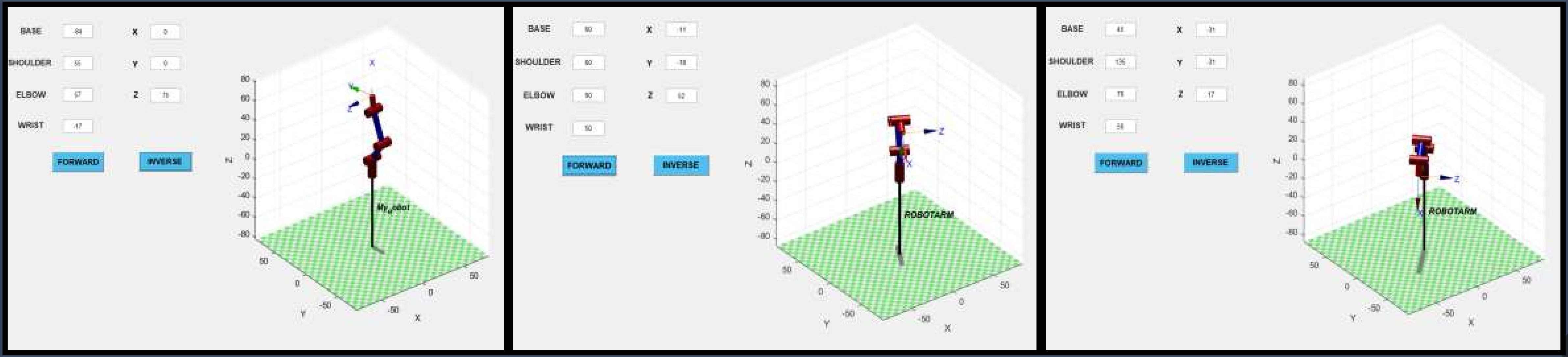






SIMULATION TEST RESULTS OF INVERSE KINEMATICS

Output Coordinate (cm)			Input Angle (degree)			
X	Y	Z	θ_1	θ_2	θ_3	θ_4
0	0	75	-84	55	57	-17
-11	-18	52	60	60	90	50
-31	-31	17	45	135	70	50

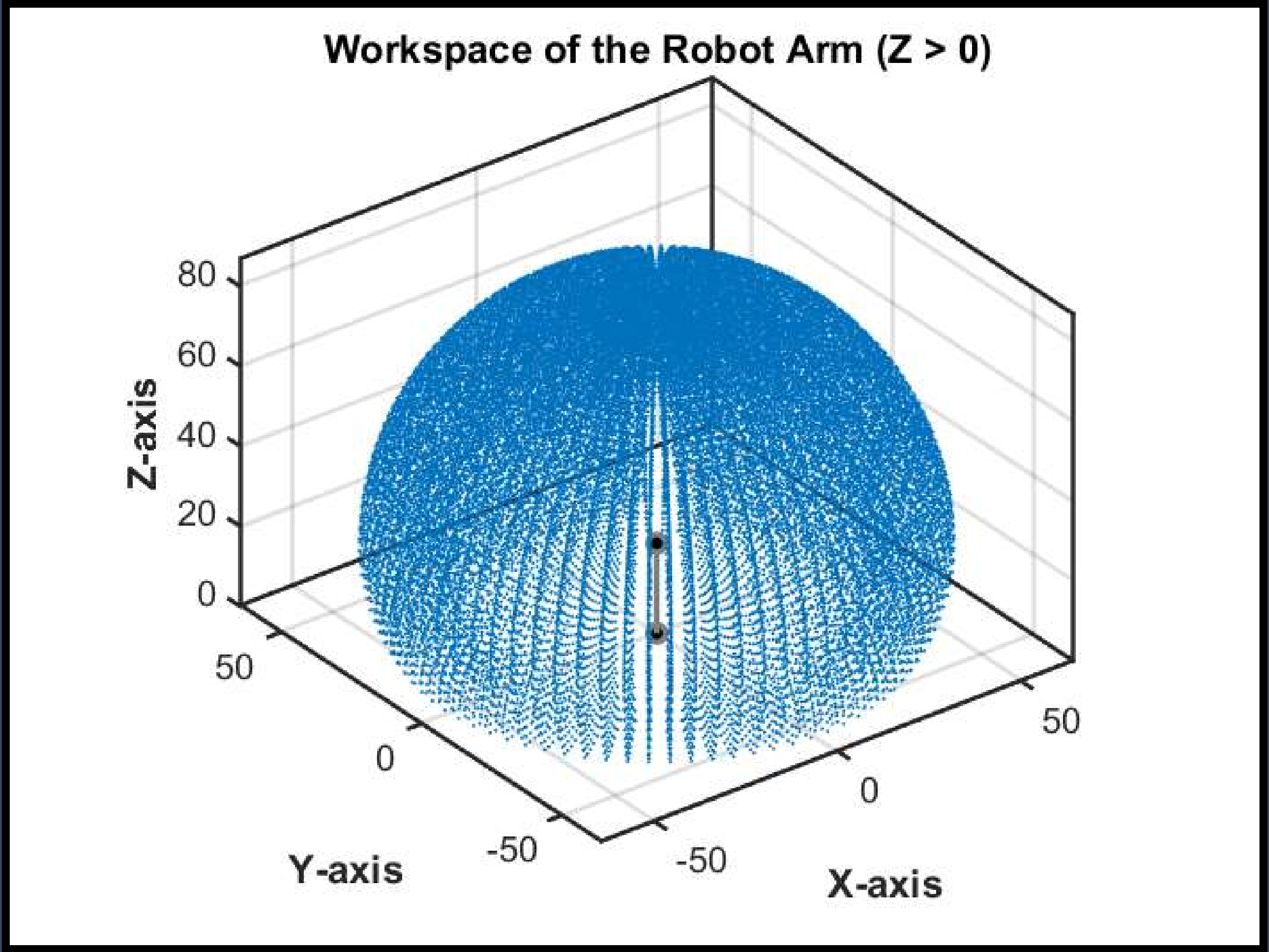


FINALIZED SET OF LINK LENGTHS AND FINALIZED DH TABLE

$L_1 = Length\ from\ base\ to\ shoulder = 22.5cm$
$L_2 = Length\ from\ shoulder\ to\ elbow = 27cm$
$L_3 = Length\ from\ elbow\ to\ wrist = 22.5cm$
$L_4 = Length\ from\ wrist\ to\ end\ effector = 15cm$

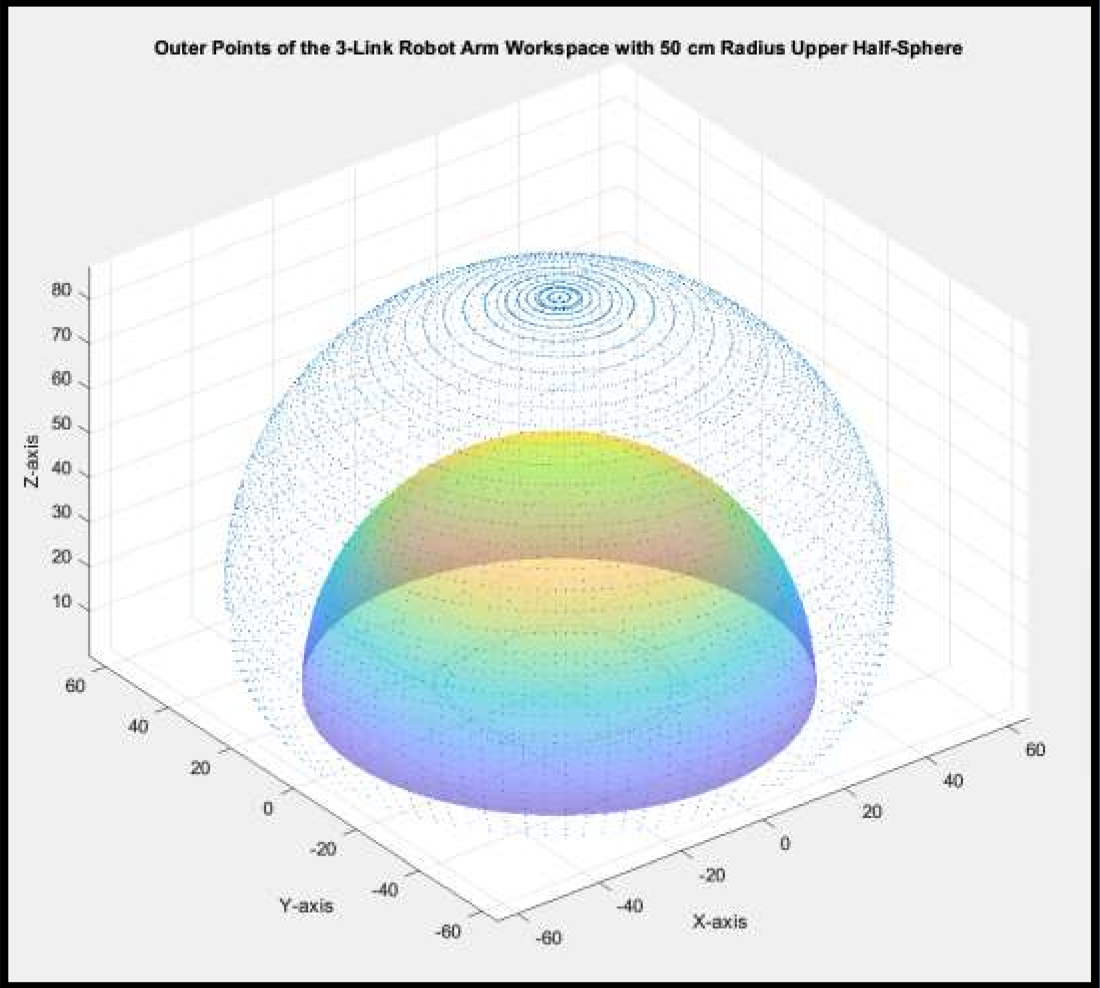
Joint	θ_i	d_i	a_i	α_i
Base	θ_1	22.5	0	90
Shoulder	θ_2	0	27	0
Elbow	θ_3	0	22.5	0
Wrist	θ_4	0	15	0

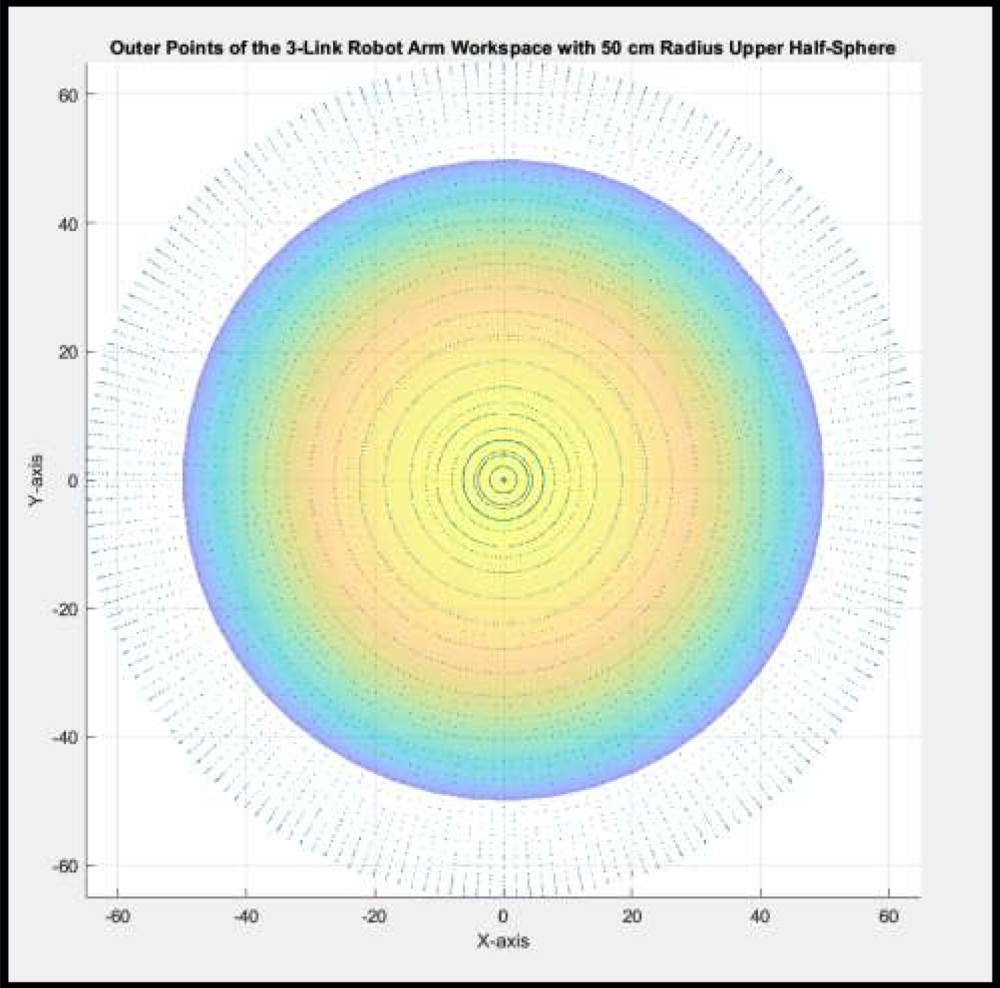
WORKSPACE ANALYSIS



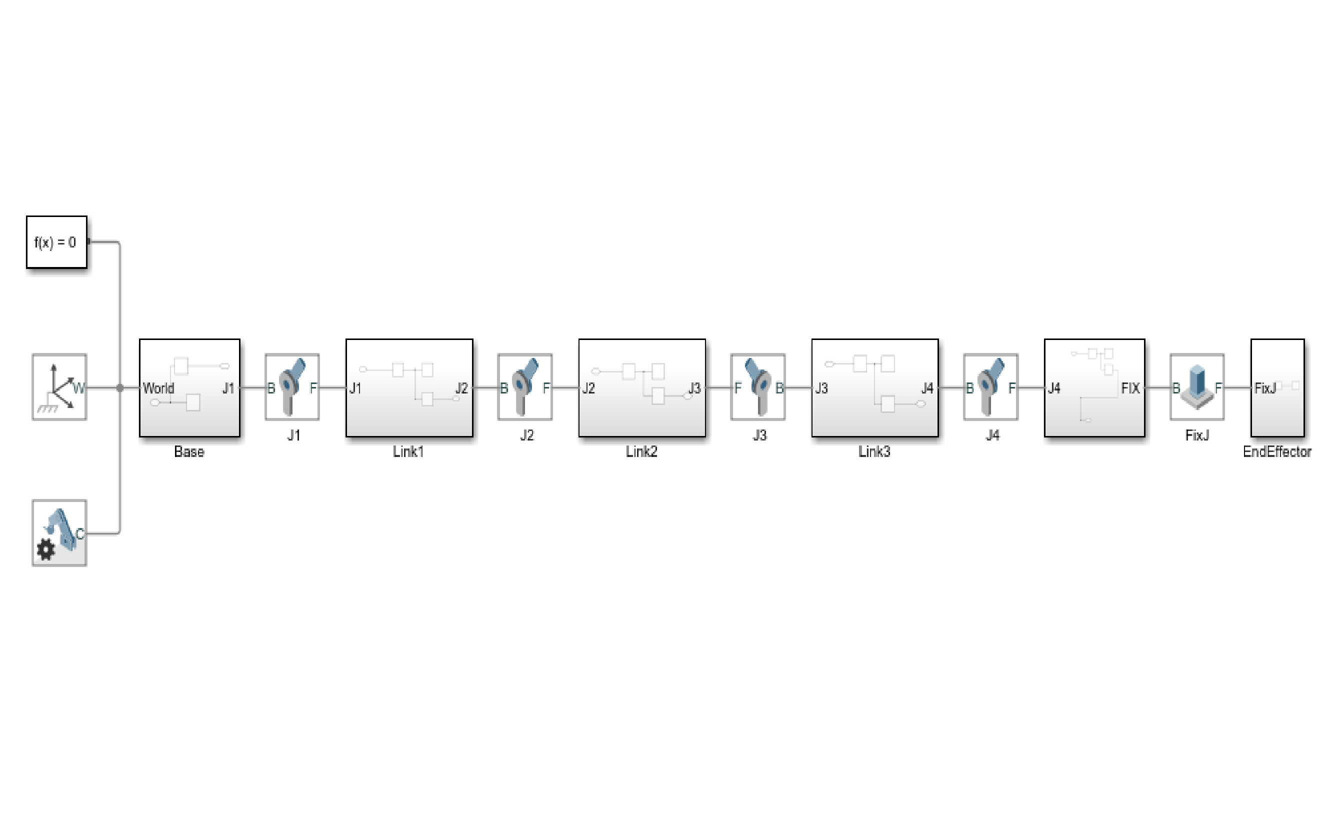
Obtained workspace of the robot-arm for the finalized link lengths

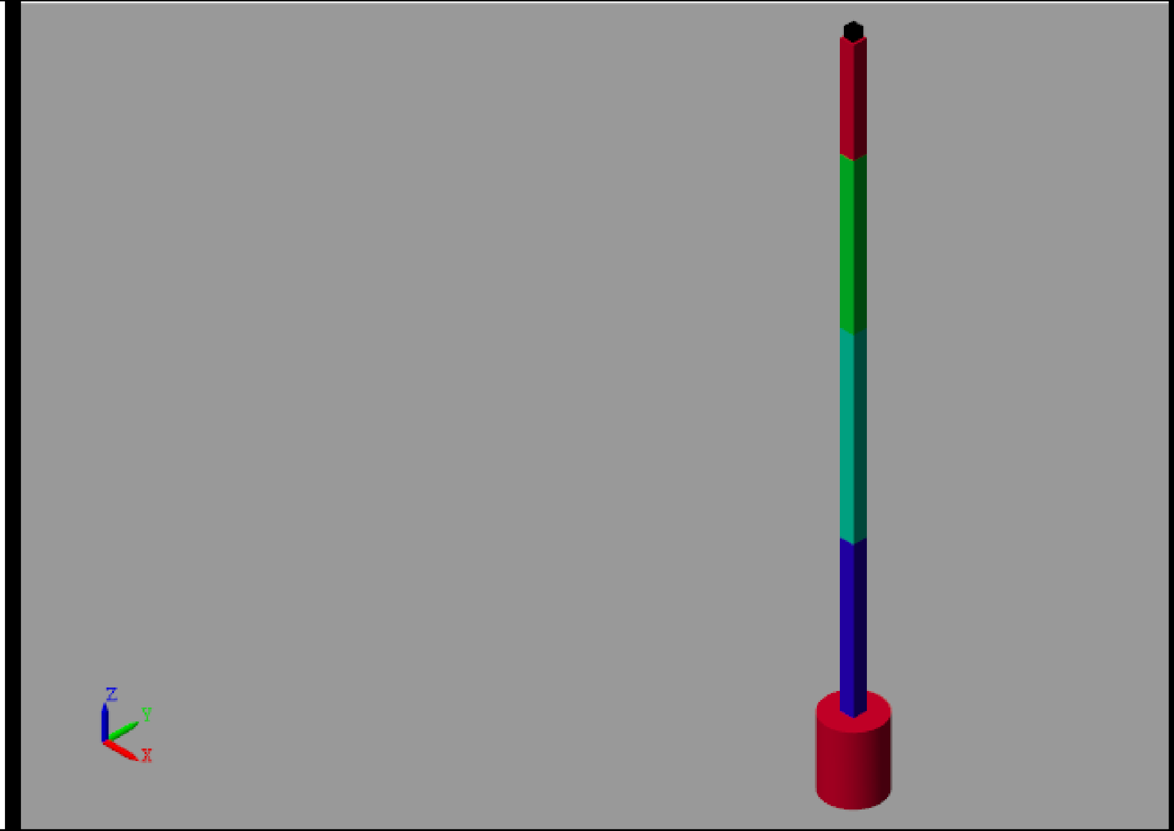
WORKSPACE JUSTIFICATION



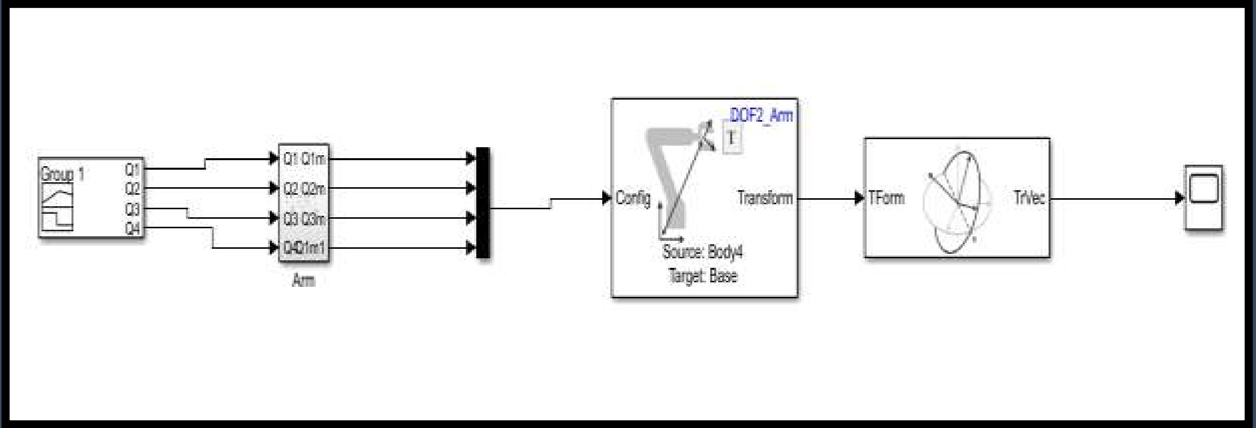


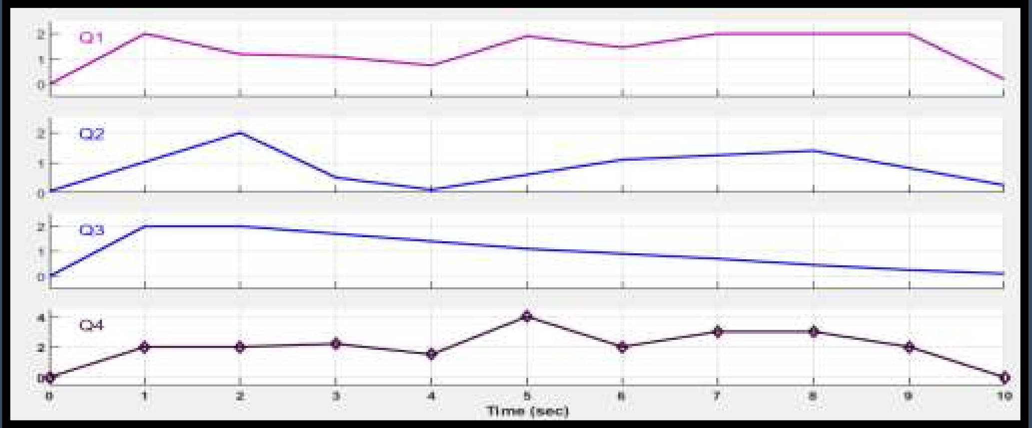
SIMULINK MODEL FOR THE ROBOT ARM

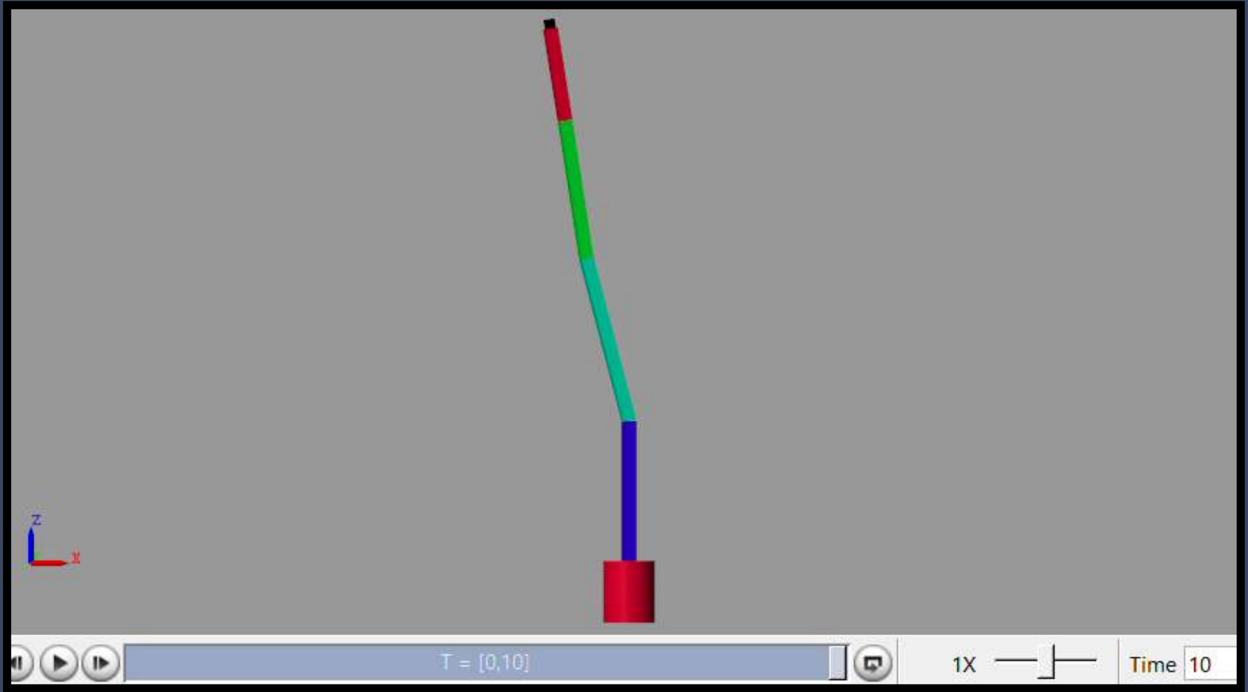


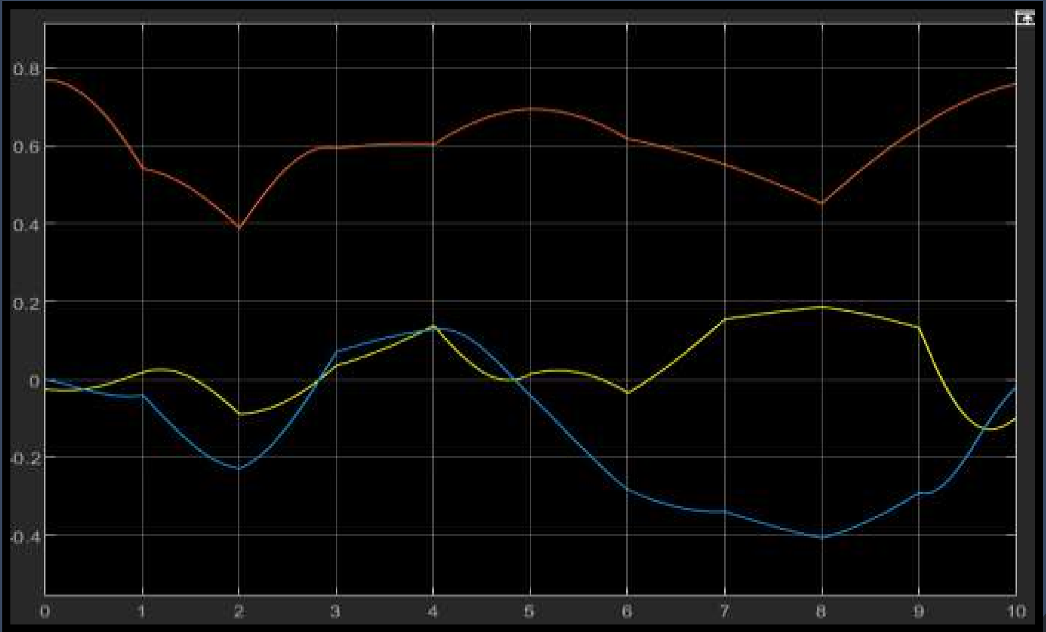


FORWARD KINEMATICS

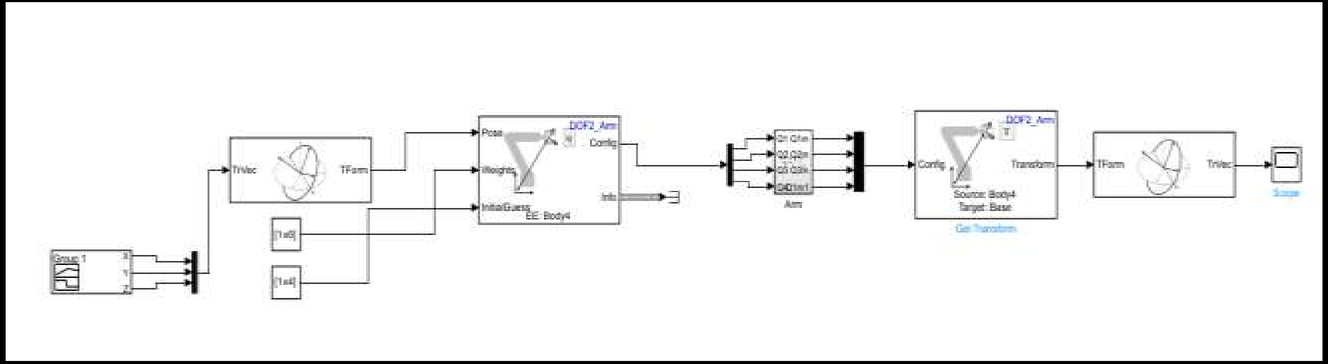


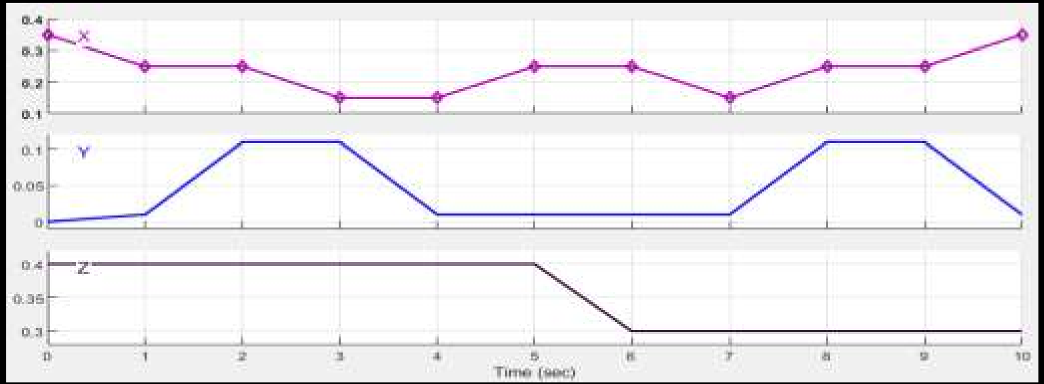


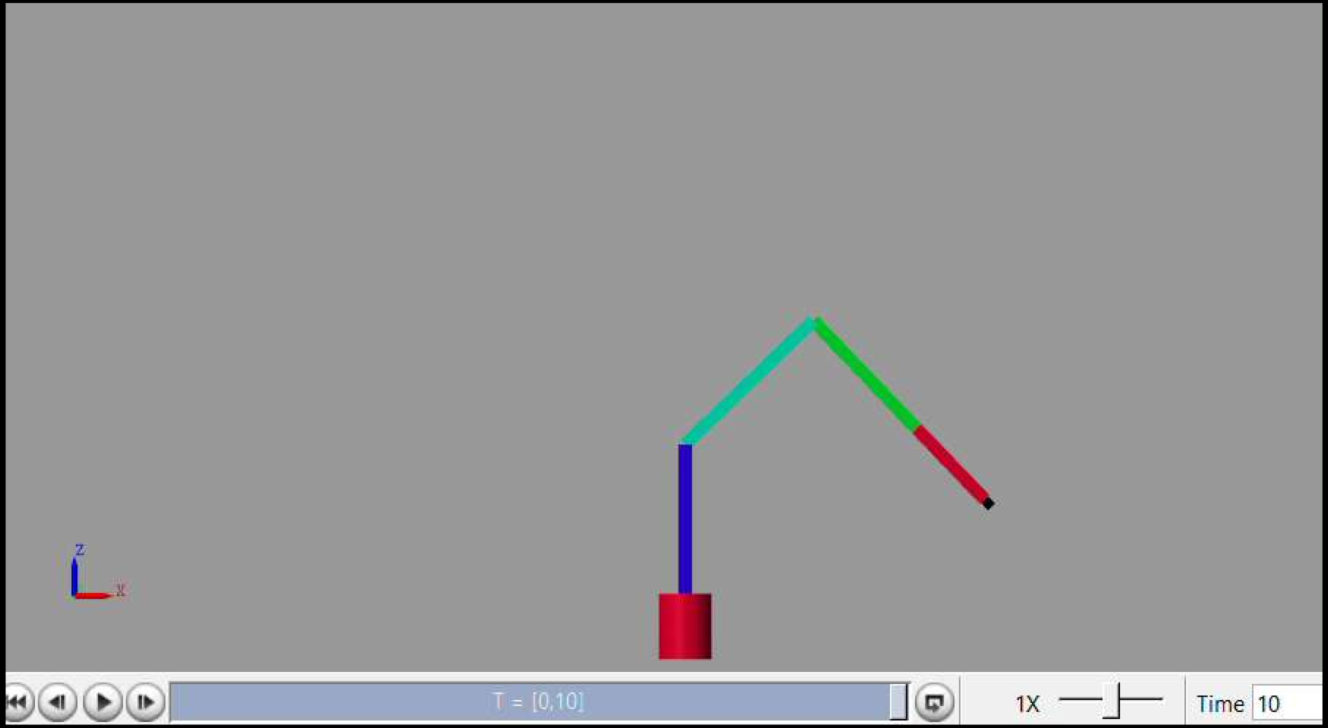


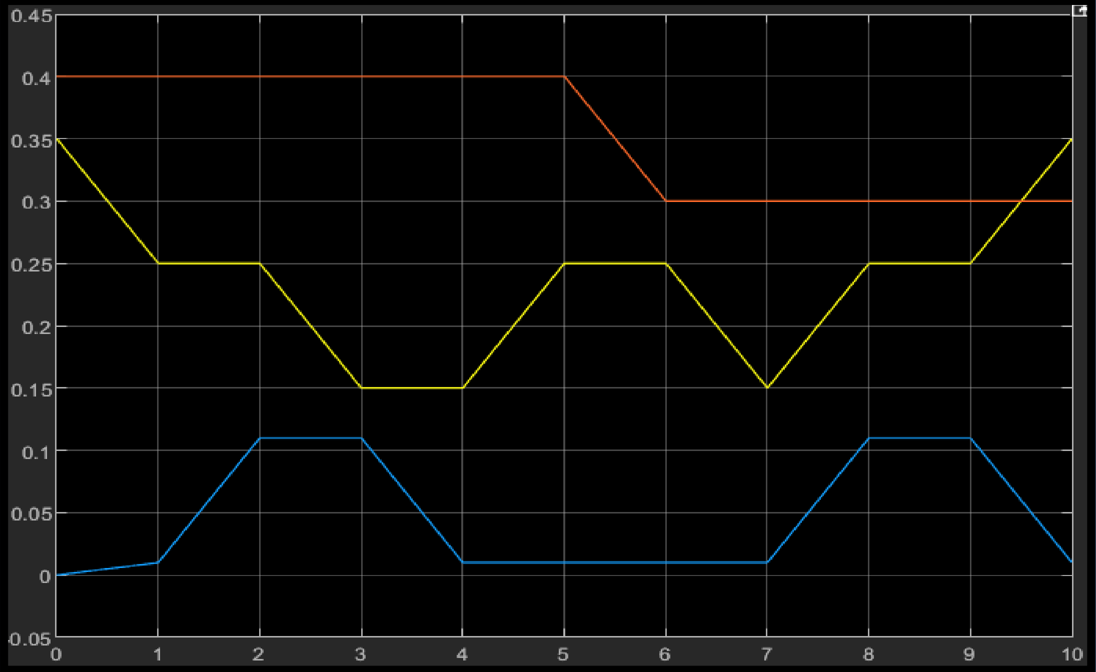


INVERSE KINEMATICS

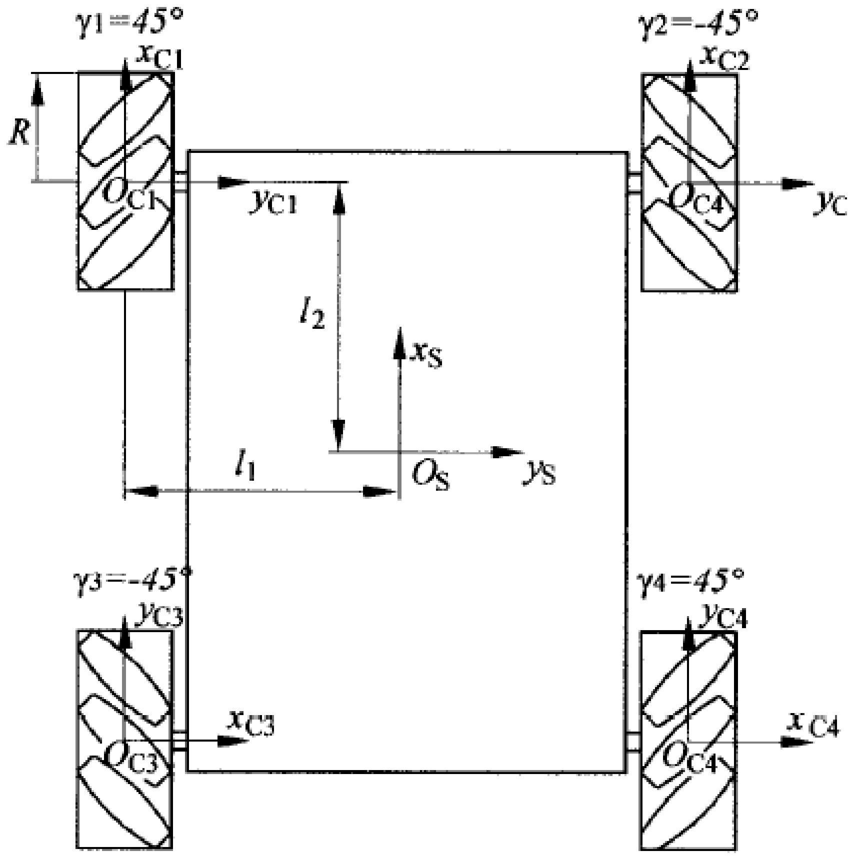








KINEMATICS – CHASSIS

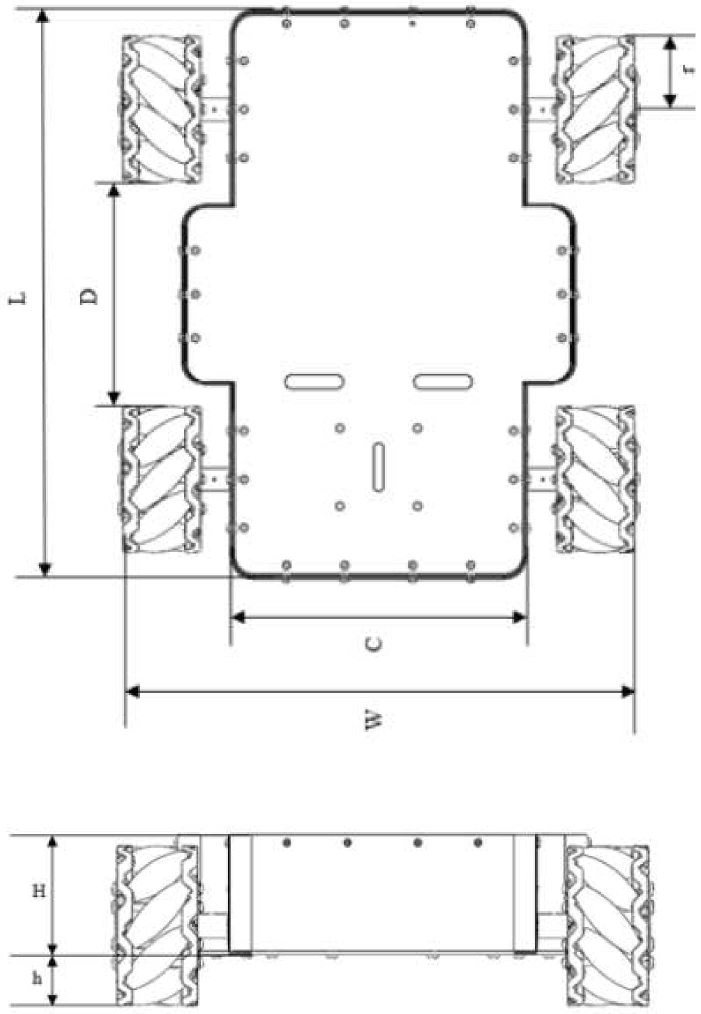


$$\begin{bmatrix} v_x \\ v_y \\ \omega_z \end{bmatrix} = \frac{R}{4}\begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & -1 & -1 & 1 \\ -\frac{1}{l_1+l_2} & \frac{1}{l_1+l_2} & -\frac{1}{l_1+l_2} & \frac{1}{l_1+l_2} \end{bmatrix} \cdot \begin{bmatrix} \omega_1 \\ \omega_2 \\ \omega_3 \\ \omega_4 \end{bmatrix}$$

$$\begin{bmatrix} \omega_1 \\ \omega_2 \\ \omega_3 \\ \omega_4 \end{bmatrix} = \frac{1}{R}\begin{bmatrix} 1 & 1 & -(l_1+l_2) \\ 1 & -1 & l_1+l_2 \\ 1 & -1 & -(l_1+l_2) \\ 1 & 1 & l_1+l_2 \end{bmatrix} \cdot \begin{bmatrix} v_x \\ v_y \\ \omega_z \end{bmatrix}$$

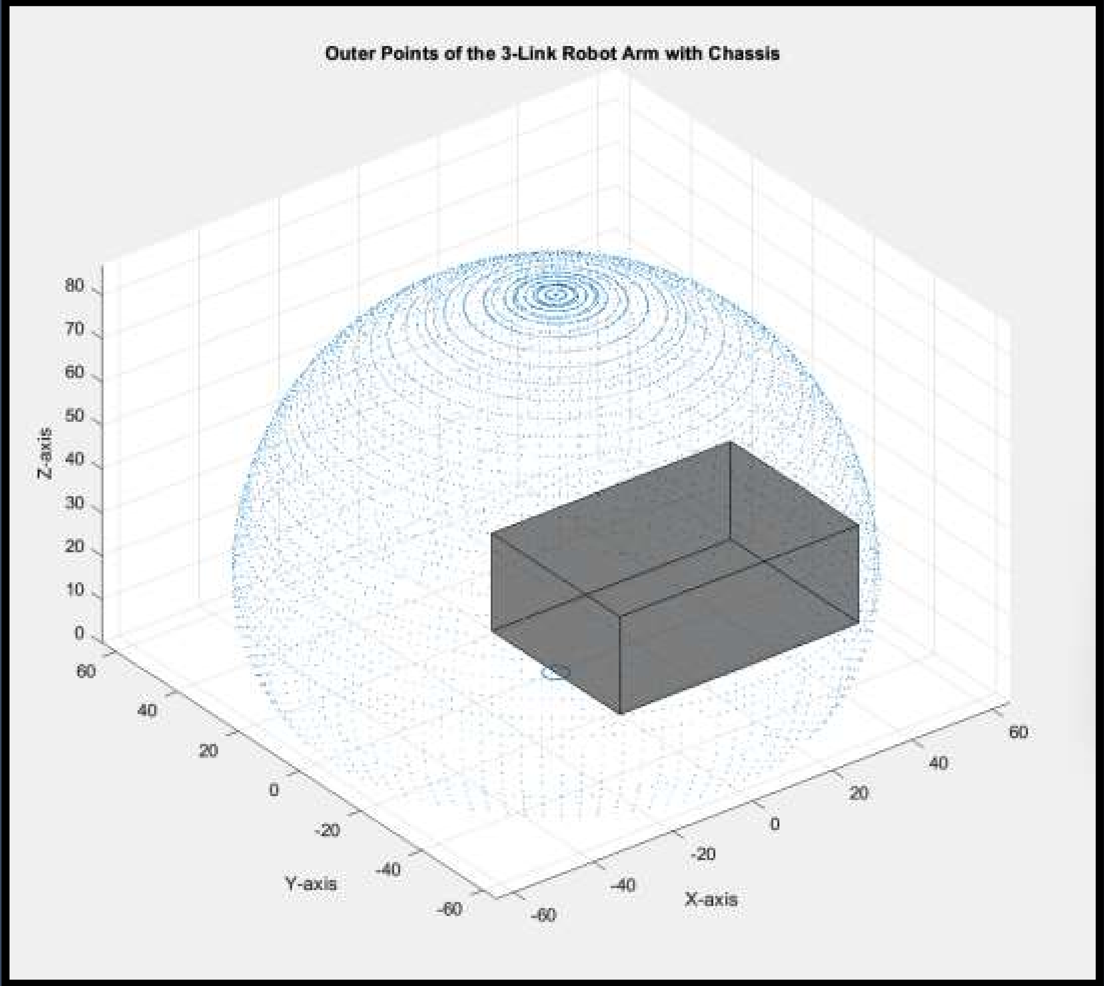
$v_x = Longitudinal\ Body\ Velocity$
$v_y = Lateral\ Body\ Velocity$
$\omega_z = Angular\ velocity\ aroung\ the\ center\ of\ robot$
$\omega_i = Angular\ velocity\ of\ the\ wheels$

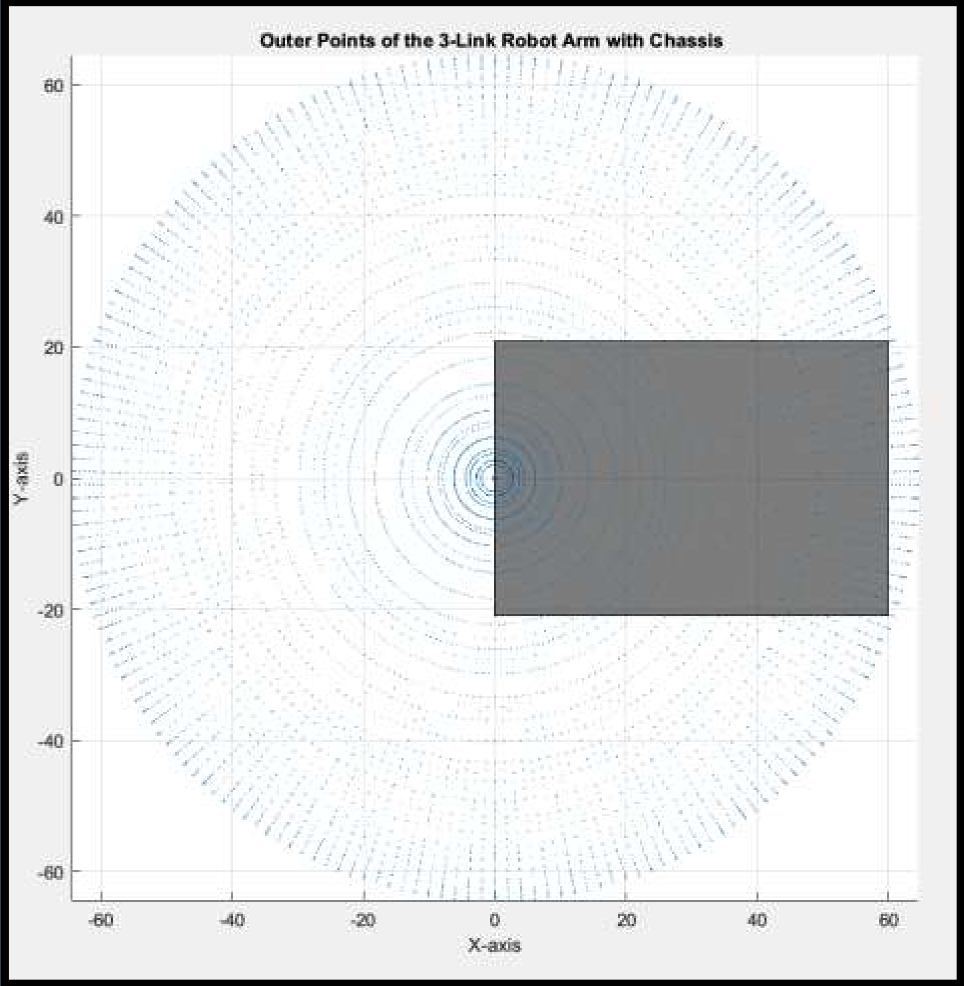
DIMENSIONS OF THE CHASSIS



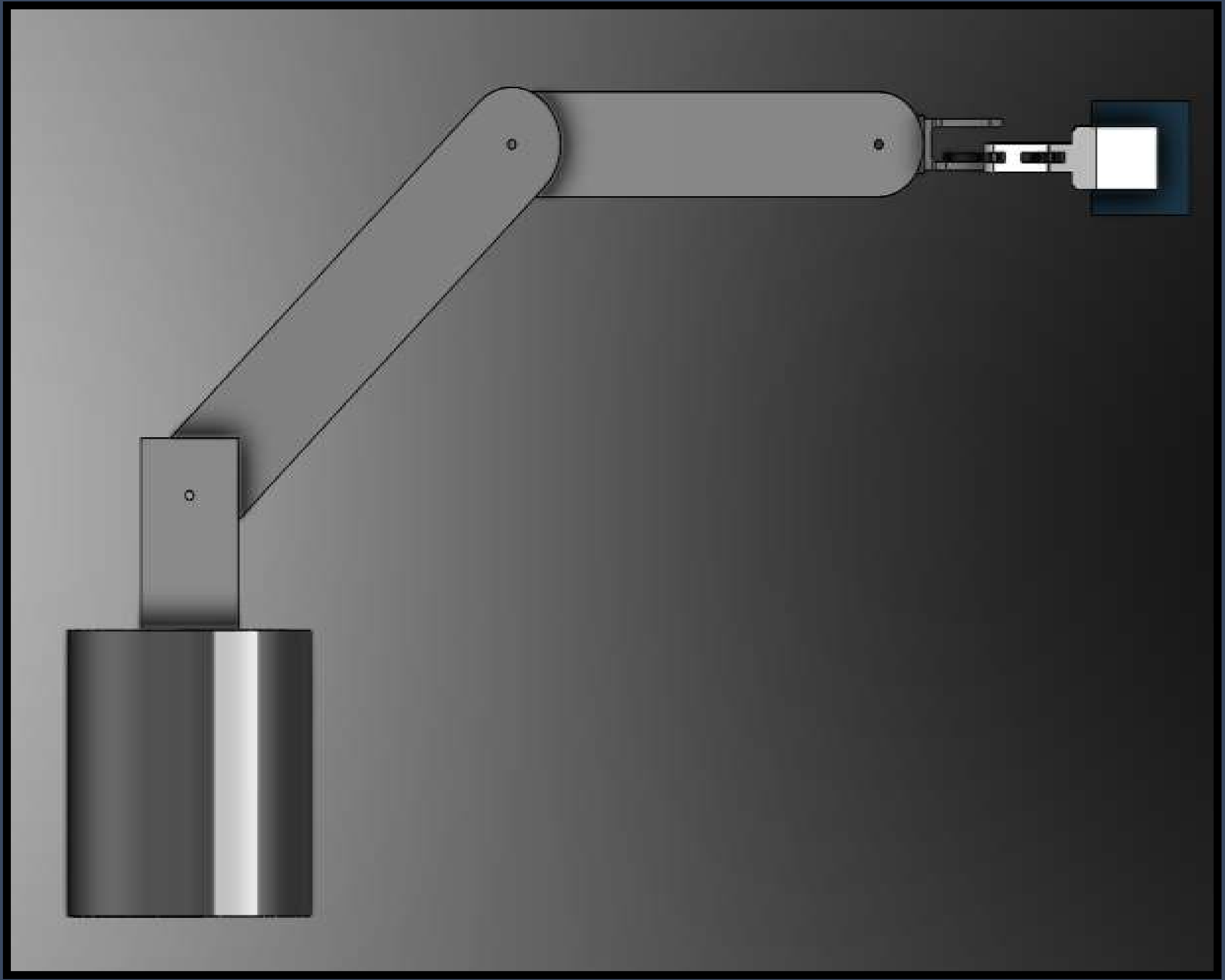
Symbol	Explanation	Value
L	Length of the Chassis	600mm
W	Width of the Chassis	420mm
C	Distance between right and left wheel	240mm
D	Distance between front and back wheel	300mm
r	Radius of the wheel	150mm
H	Chassis height	113mm
h	Ground Clearance	50mm

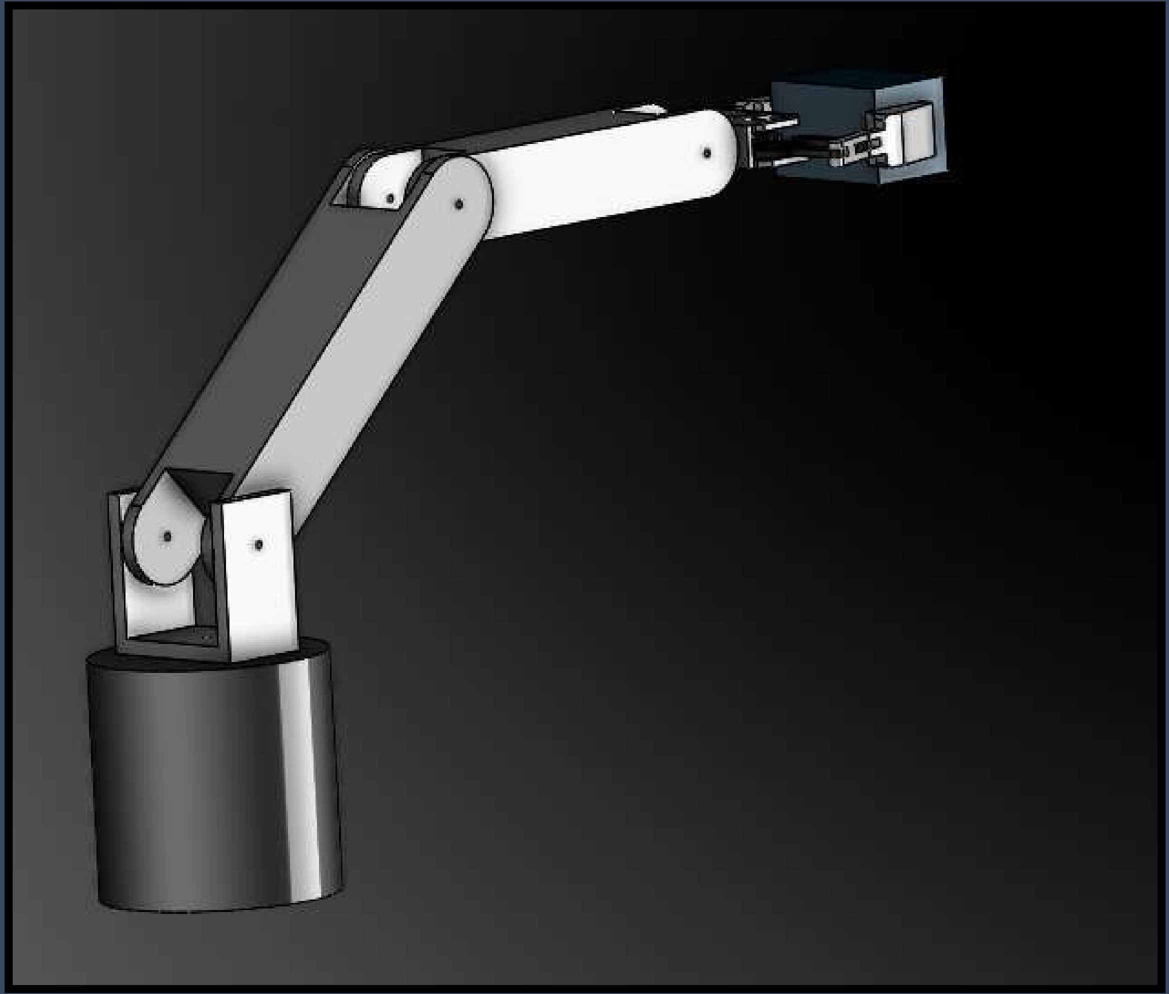
WORKSPACE VISULIZATION WITH THE CHASSIS DIMENSIONS





INITIAL SOLIDWORK DESIGN – ROBOT ARM





MATERIAL SELECTION – ROBOT ARM

CHOSEN MATERIAL – PA TYPE 6

- Lightweight: Ensures ease of movement and efficiency in the manipulator arm.
- Strength and Toughness: Provides high tensile strength and impact resistance, suitable for handling loads.
- 3D Printability: Compatible with FDM and SLS methods, allowing precise and durable 3D prints.

Direct Plastics

Nylon Extruded 6 Black

PA6 (Polyamide 6)
Colour: Natural
Fillers: Molybdenum Disulfide
Density: 1.14g/cm^3

Material Data Sheet

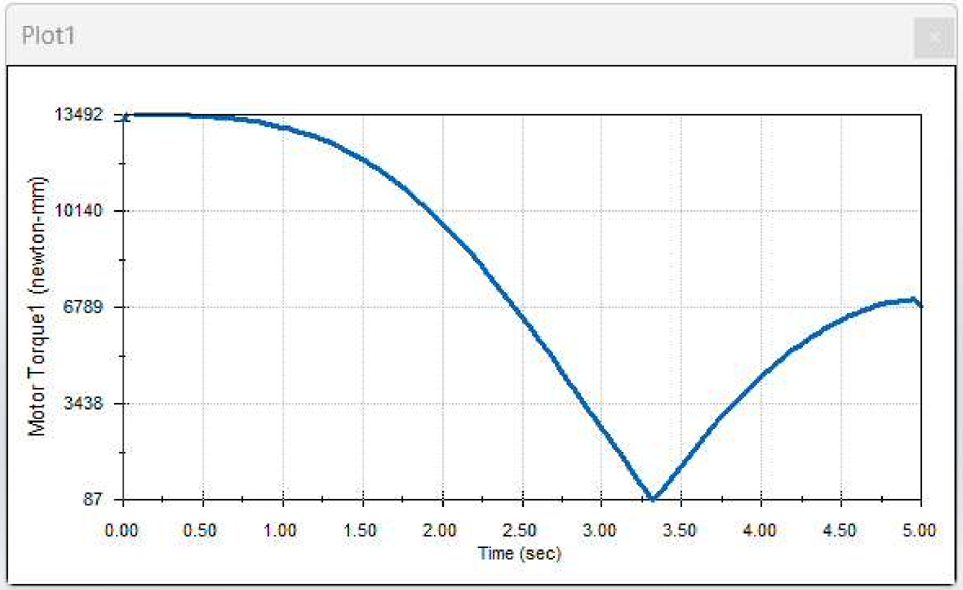
Mechanical Properties	Parameter	Value	Unit	DIN/EN/ISO
Modulus of elasticity (tensile test)	1mm/min	3300	MPa	527-2
Tensile strength	50mm/min	84	MPa	527-2
Tensile strength at yield	50mm/min	82	MPa	527-2
Elongation at Yield	50mm/min	5	%	527-2
Elongation at break	50mm/min	37	%	527-2
Flexural strength	2mm/min 10N	110	MPa	178
Modulus of elasticity (flexural test)	2mm/min 10N	3100	MPa	178
Compression Strength	1%/2% 5mm/min 10N	17/32	MPa	604
Compression modulus	5mm/min 10N	2900	MPa	604
Impact strength (Charpy)	Max. 7,5J	N.B.	kJ/m^2	179-1eU
Notched impact strength (Charpy)	Max. 7,5J	5	kJ/m^2	179-1eA
Ball indentation hardness	-	160	MPa	2039-1

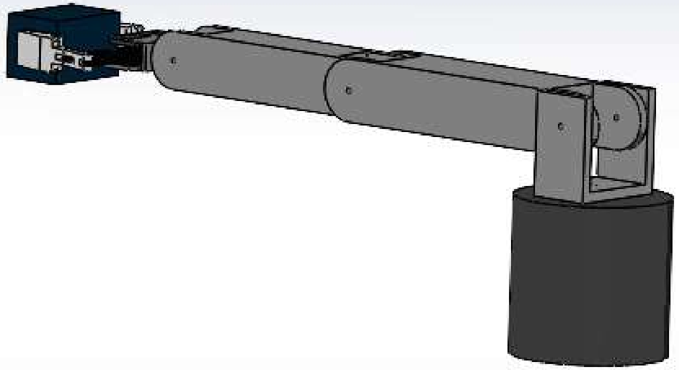
Thermal Properties	Parameter	Value	Unit	DIN/EN/ISO
Glass transition temperature	-	51	°C	53765
Melting temperature	-	220	°C	53765
Service temperature	Short term	160	°C	-
Service temperature	Long term	100	°C	-
Thermal expansion (CLTE)	23-60°C, Long	8	$10^{-5}K^{-1}$	11359-1;2
Thermal expansion (CLTE)	23-100°C, Long	138	$10^{-5}K^{-1}$	11359-1;2
Specific heat	-	1.6	J/(g*K)	22007-4:2008
Thermal conductivity	-	0.37	W/(K*m)	22007-4:2008

Electrical properties	Parameter	Value	Unit	DIN/IEC
Surface resistance	-	$>10^{12}$	Ω	60093

Other properties	Parameter	Value	Unit	DIN/EN/ISO/IEC
Water absorption	24h/96h (23°C)	0.3/0.6	%	62
Resistance to hot water/bases	-	(+)	-	-
Resistance to weathering	-	(+)	-	-
Flammability (UL94)	Corresponding to	HB	-	60695-11-10

MOTOR TORQUE ESTIMATION – SHOULDER JOINT



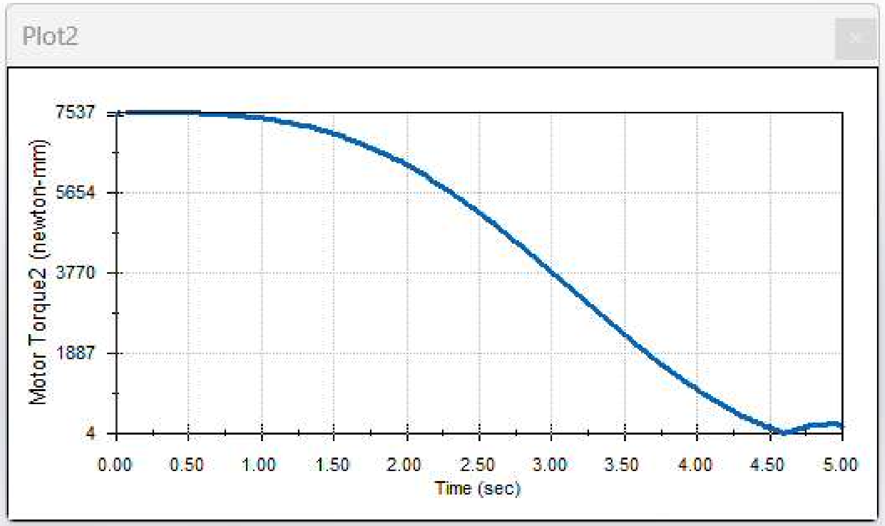


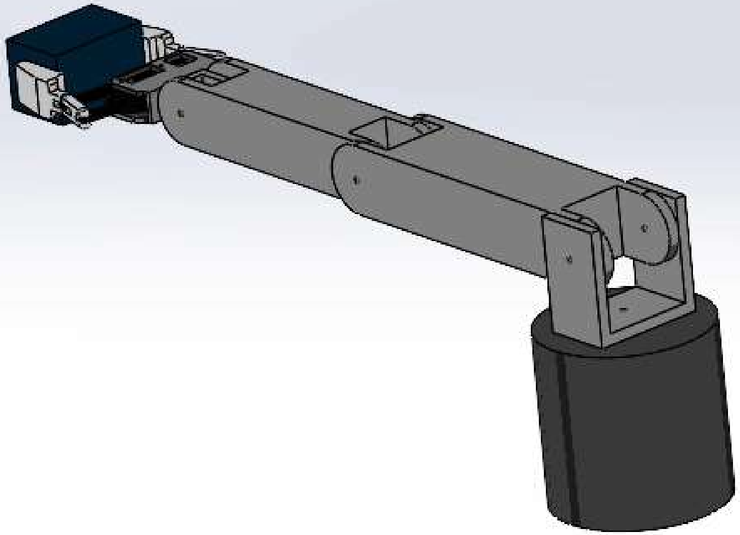
MOTOR SELECTION – SHOULDER JOINT

Selected Motor: GXServo X150

x150
Pulse Width:500μs-2500μs =180°
OperatingSpee:(12V):0.16sec60°
OperatingSpeed:(13V):0.15sec60
OperatingSpeed:(14V)0.14sec60°
Stall Torque(12V):150kg.cm
StallTorque(13V):160kg.cm
Motor:brushless Dead band:3μs
Ball Bearing:2BBWorking
Frequence:1520μs/330hz
Dimensions:65*30*58mm
Weight:220g

MOTOR TORQUE ESTIMATION – ELBOW JOINT





MOTOR SELECTION – ELBOW JOINT

Selected Motor: GXServo X100

X100

Pulse Width:500μs-2500μs =180°

Operating Speed:(6V):0.135sec60°

OperatingSpeed(7.4V):0.11sec60

Operating Speed:(8.4V)0.1sec60°

Stall Torque(6V):90kg.cm

Stall Torque(7.4V):100kg.cm

Stall Torque(8.4V) :112kg.cm

Motor:brushless Dead band:3μs

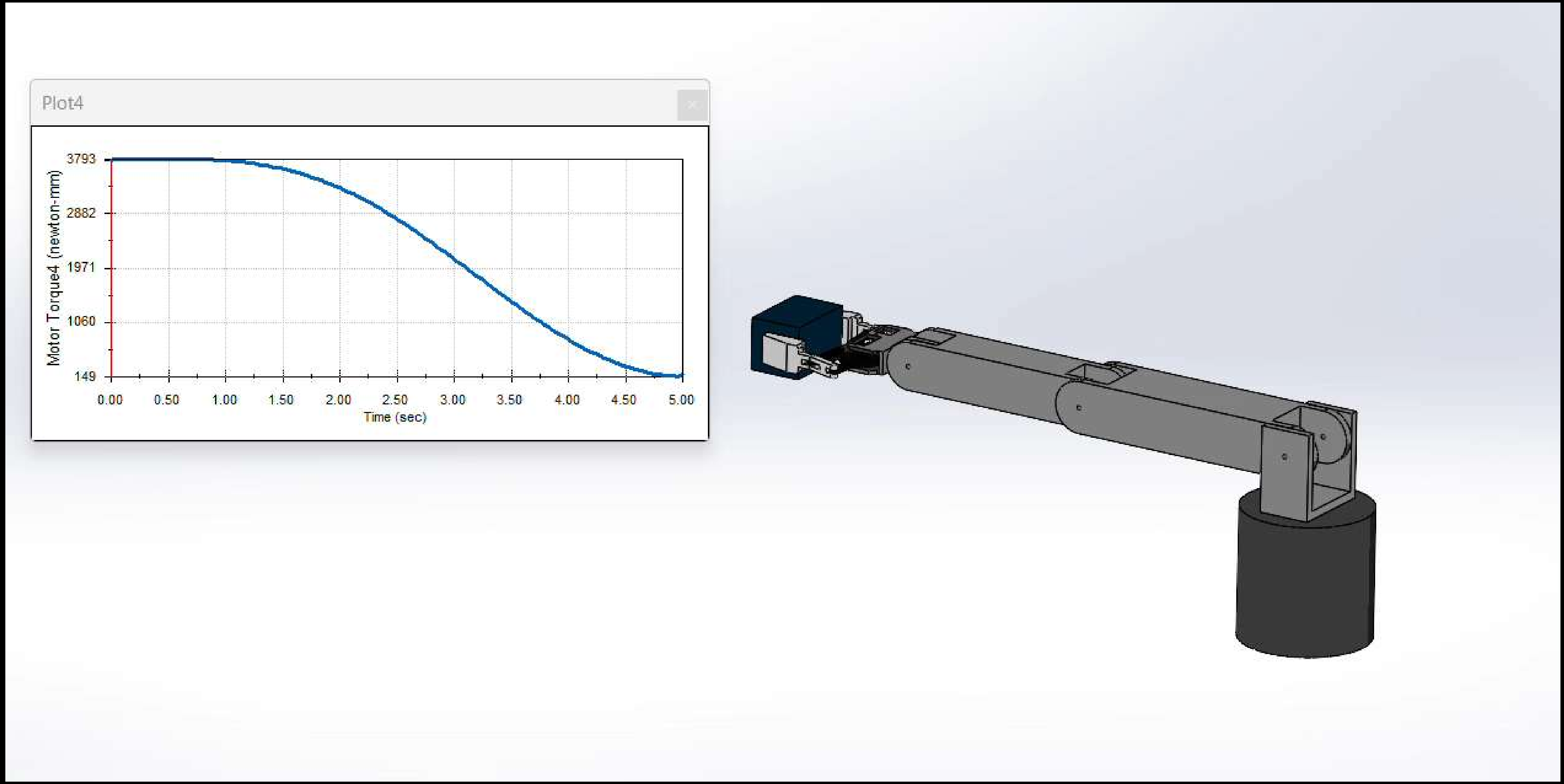
Ball Bearing:2BBWorking

Frequence:1520μs/330hz

Dimensions:65*30*58mm

Weight:220g

MOTOR TORQUE ESTIMATION – WRIST JOINT

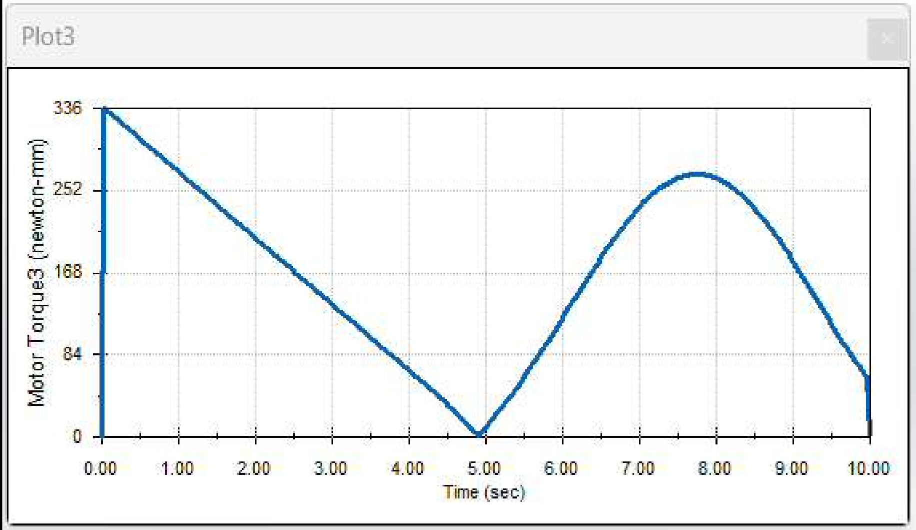


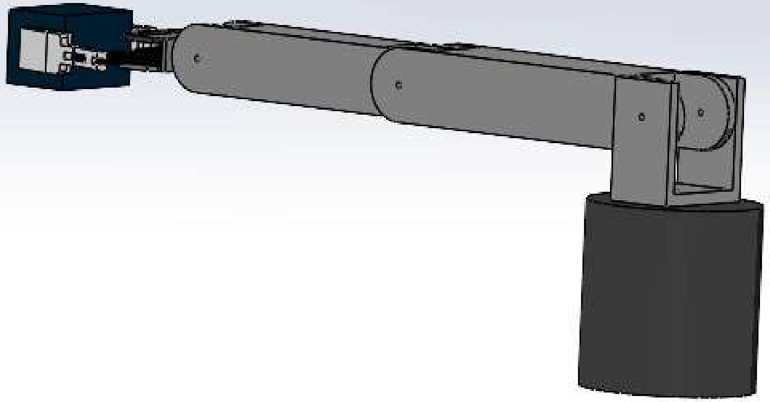
MOTOR SELECTION – WRIST JOINT

Selected Motor: Flash hobby 50KG CLS4050RP

item	value
Warranty	3months-1year
Place of Origin	Guangdong China
Brand Name	Flash Hobby
Model Number	CLS4050RP
Usage	BOAT, Car, Electric Bicycle, FAN, Home Appliance
Type	Brushless Motor
Torque	38.0/50.0
Construction	Permanent Magnet
Commutation	Brushless
Protect Feature	Waterproof
Speed(RPM)	0.11/0.15
Continuous Current(A)	custom
Efficiency	IE 4
Size:	40×20×40.50mm
Weight:	80g±10g(without servo horn)
Gear:	Steel Gears
Operating speed:	0.11sec/60° @8.4V
Stall torque:	50.0kg-cm/694 oz-in @8.4V
Motor Type:	Coreless Motor
Case Material:	CNC AL6061 Aluminum Case
Connector Wire Length:	300MM JR Plug
torque(kg-cm)	38.0/50.0
Volts	6~8.4V

MOTOR SELECTION – BASE JOINT



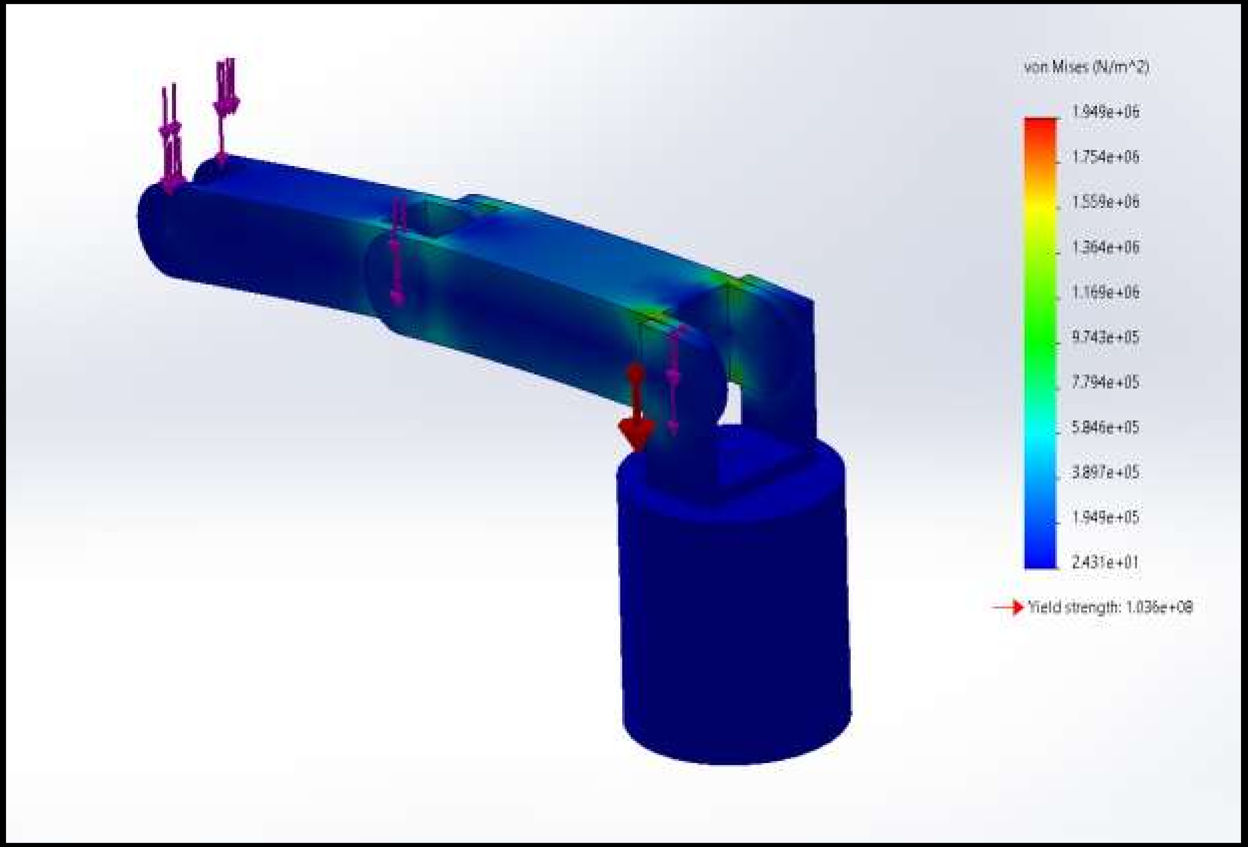


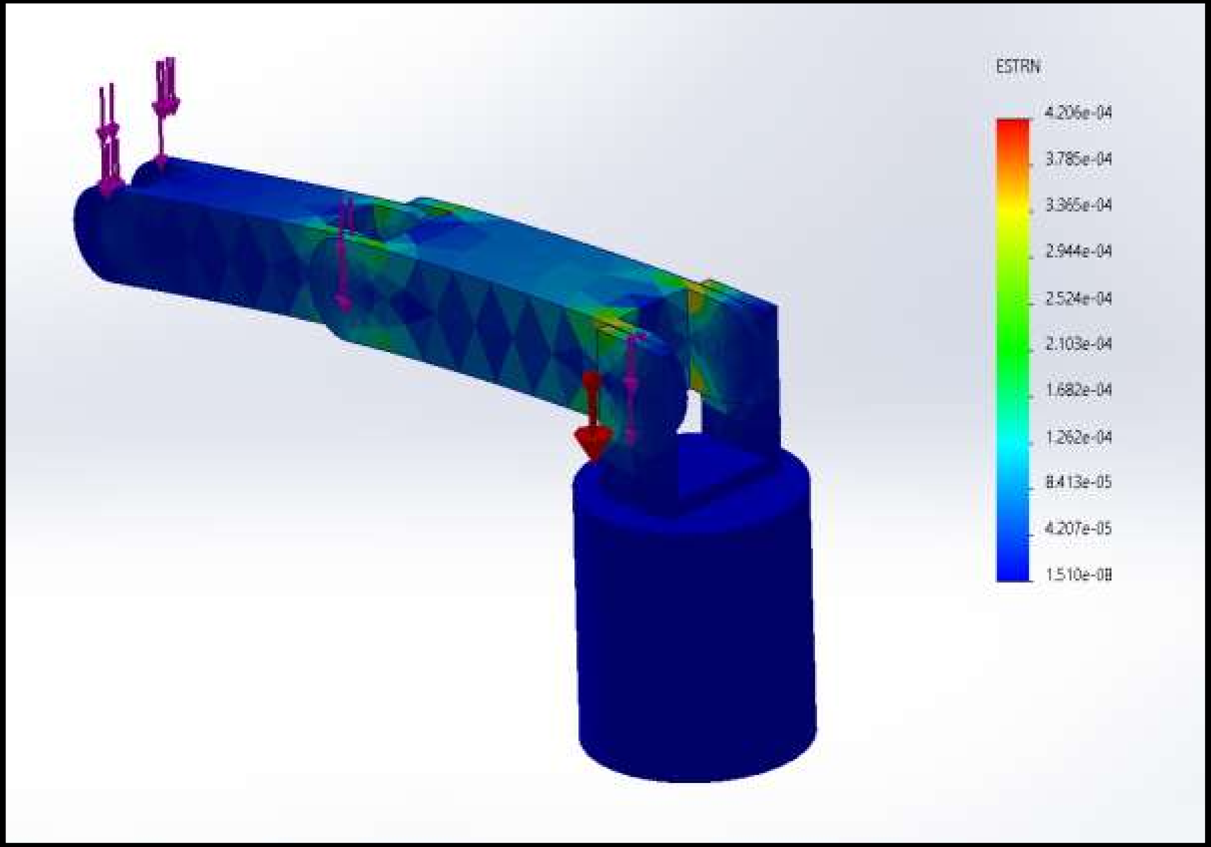
MOTOR SELECTION – BASE JOINT

Selected Motor: DS3218MG

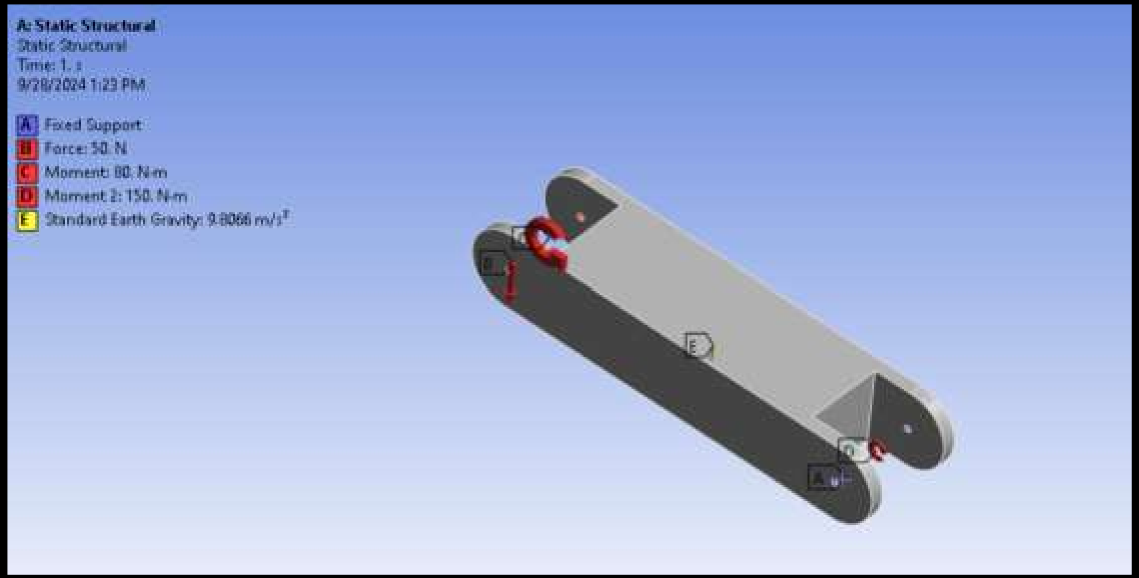
Item Type: Motor Servo
Material: Metal, plastic
Model: DS3218MG
Colour: Black
Working Voltage: 4.8-6.8V DC
Torsion (5V): 19kg/cm
Torsion (6.8V): 21.5kg/cm
Speed: 0.16s/60° (5V), 0.14s/60°(6.8V)
Reduction Ratio: 310:1
Rudder Specification: 25T/ψ5.80
Gear Ratio: 275
Pulse Width Range: 500-2500 μsec
Working Frequency: 50-330Hz
Neutral Position: 1500μs
Controllable Angle: 270°
Angle: 90°
Dead Time: 3μs
Drive Mode: PWM
Motor Type: DC Motor
Gear Type: Plastic, Aluminum Alloy, Electronic Components
Size: Approx.41x40x20mm/1.6x1.57x0.8in
Wiring:
Red: Positive
Black and Brown: Negative
Yellow and White: Signal wire
Compatible: Suitable for 1/10 1/8 RC Car Truck Boat Airplane Robot

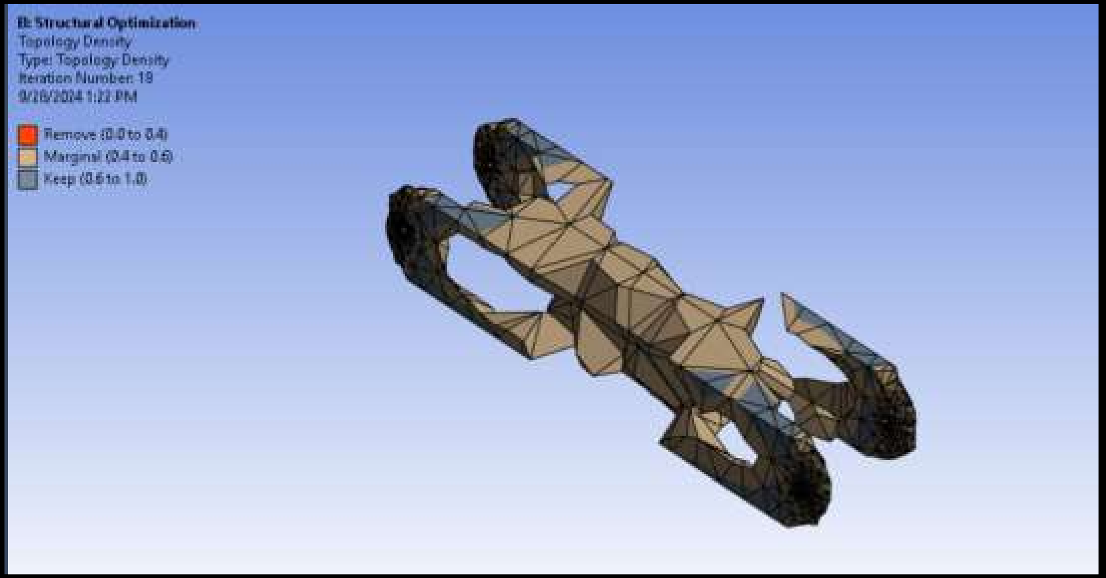
INITIAL STRESS AND STRAIN DISTRIBUTION

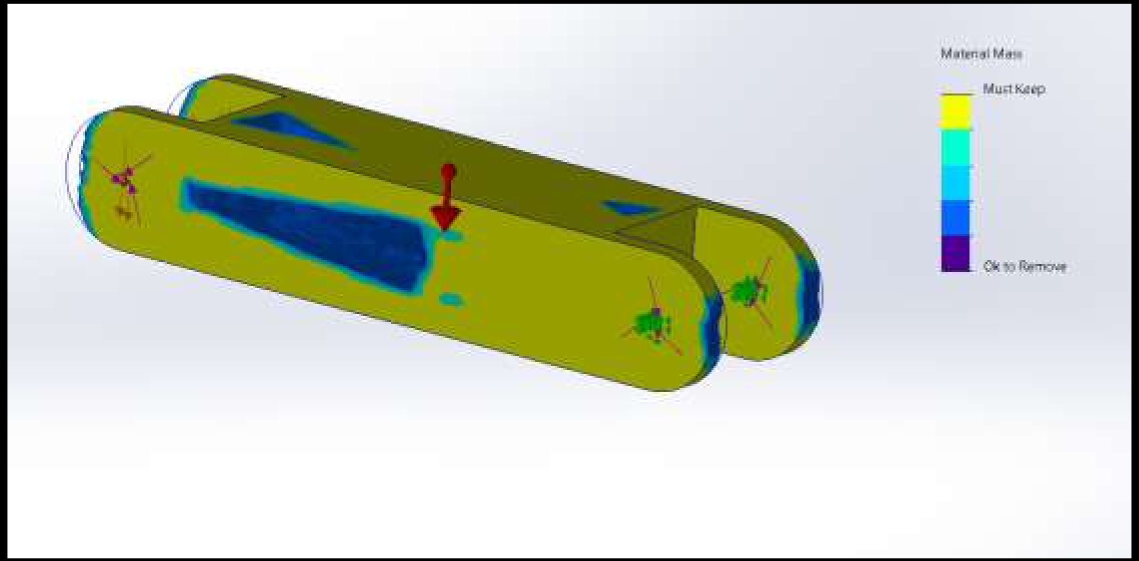


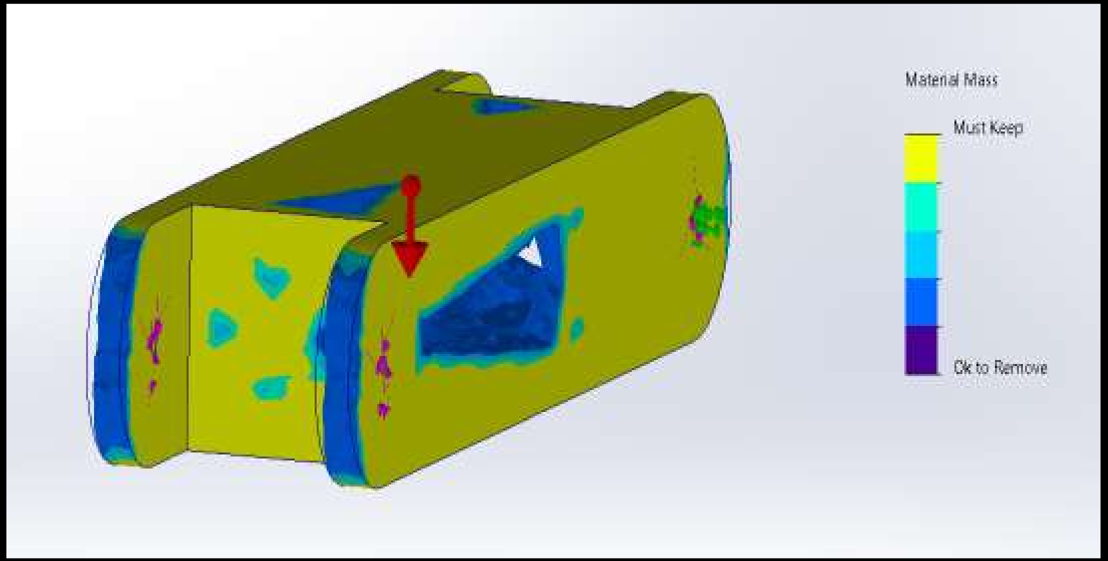


TOPOLOGY OPTIMIZATION FOR LINK 1

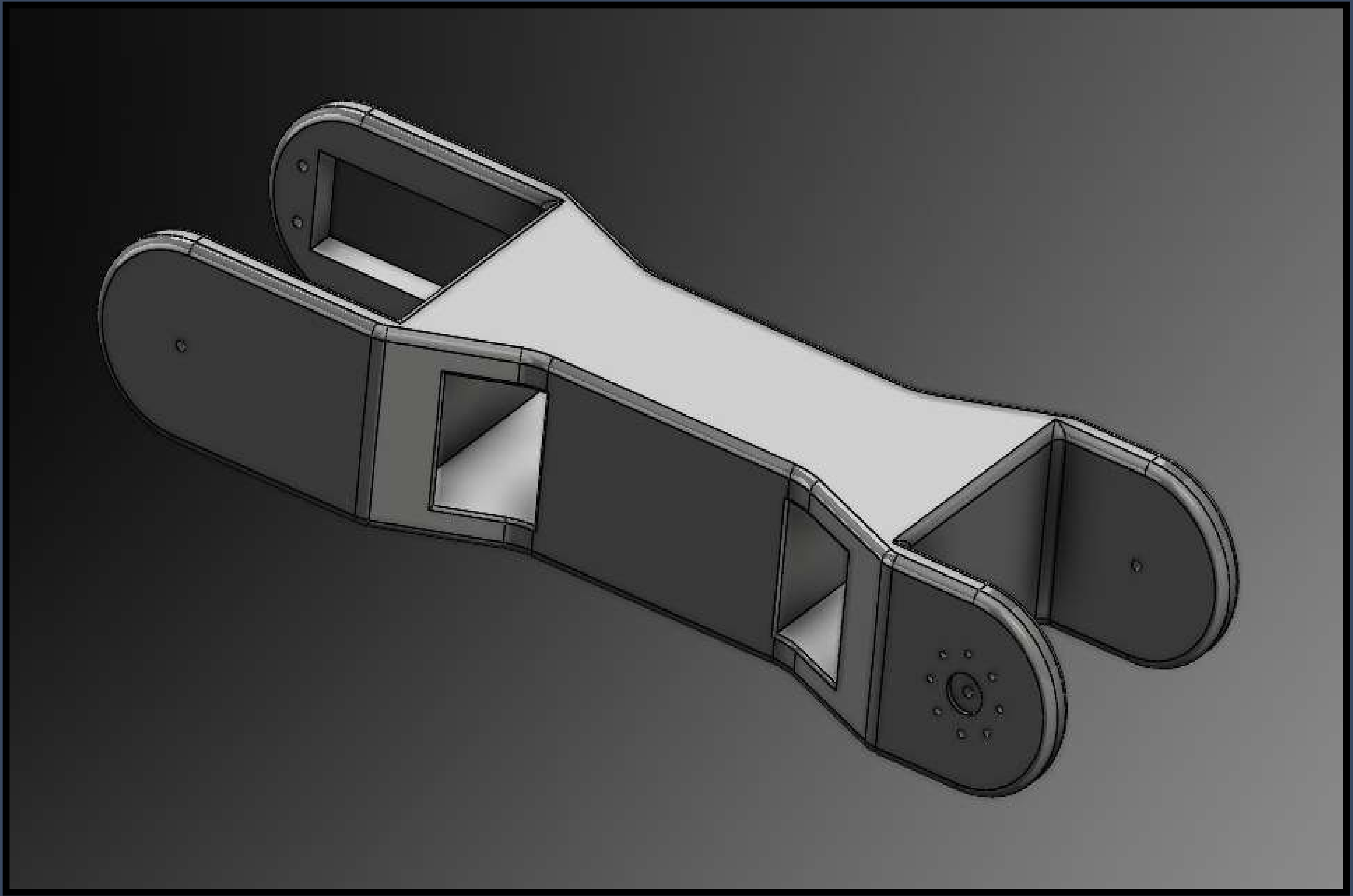


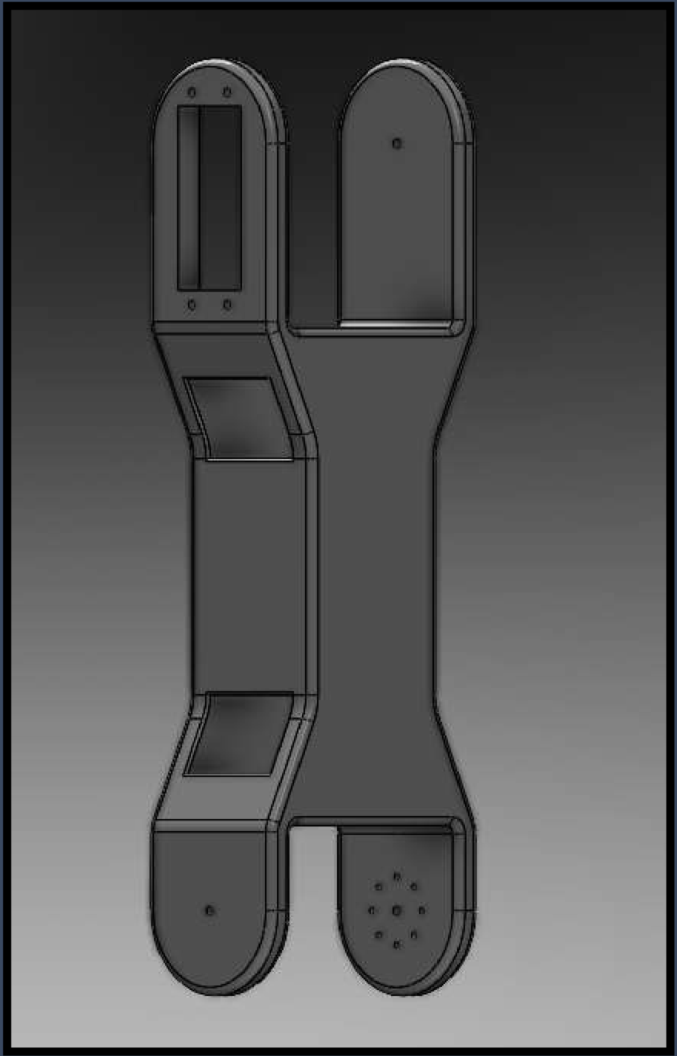




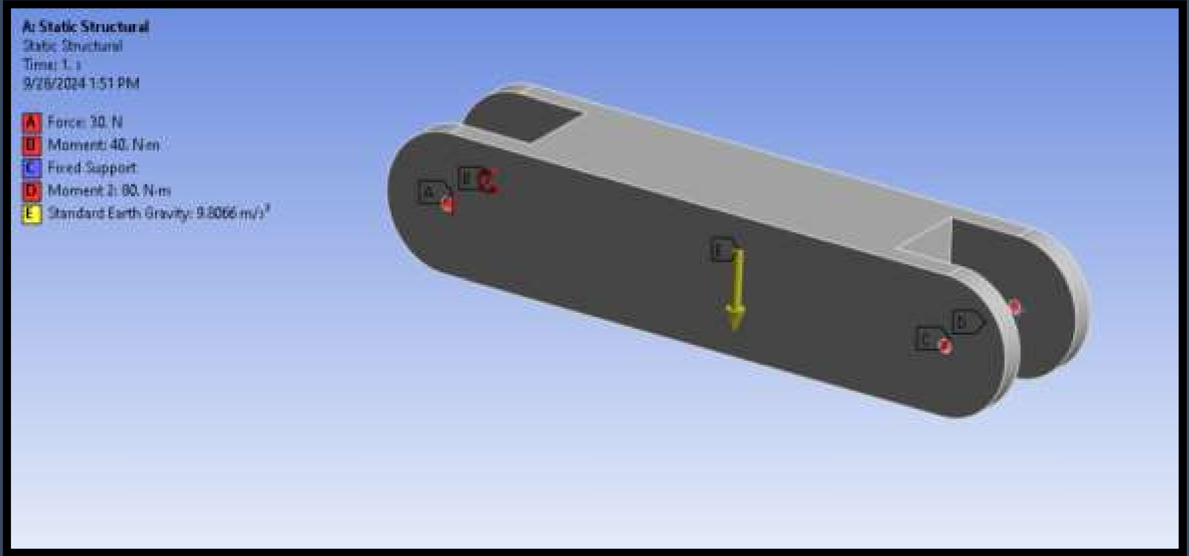


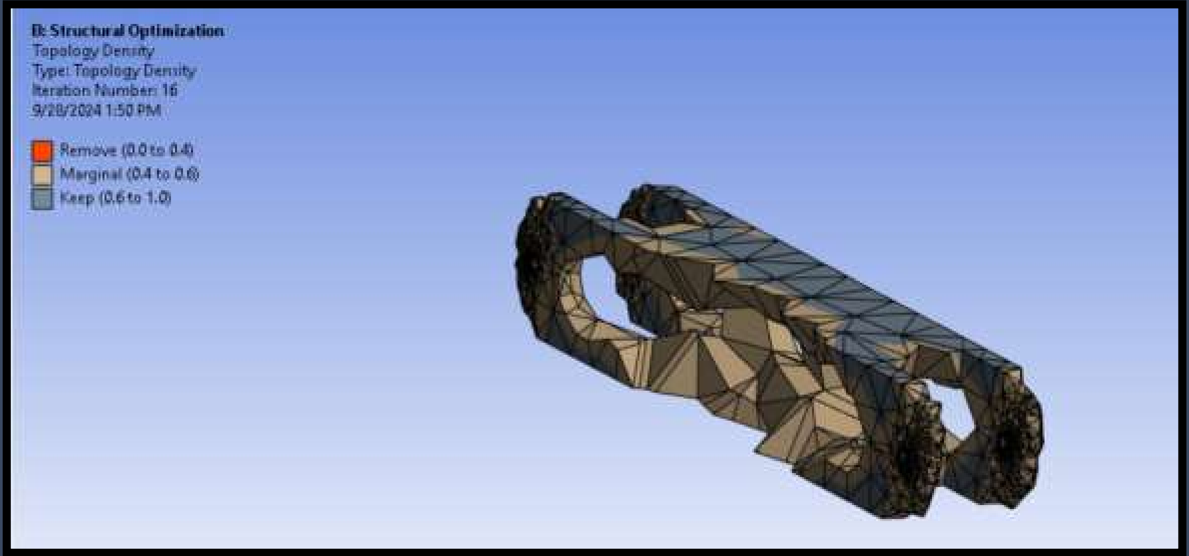
OPTIMIZED DESIGN FOR LINK 1

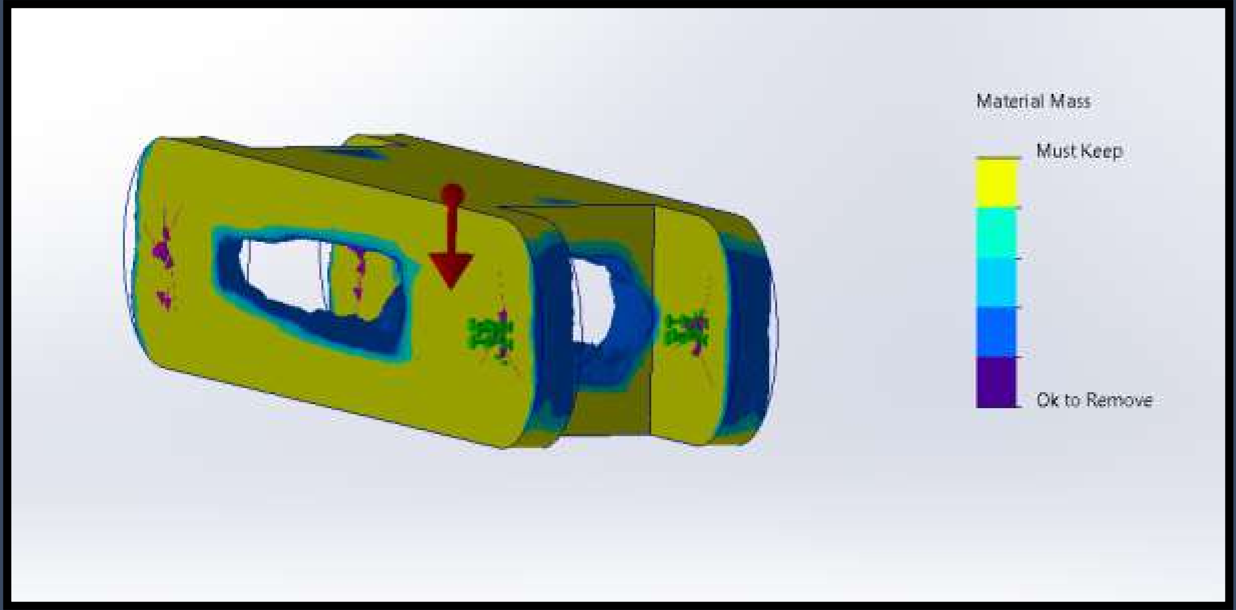




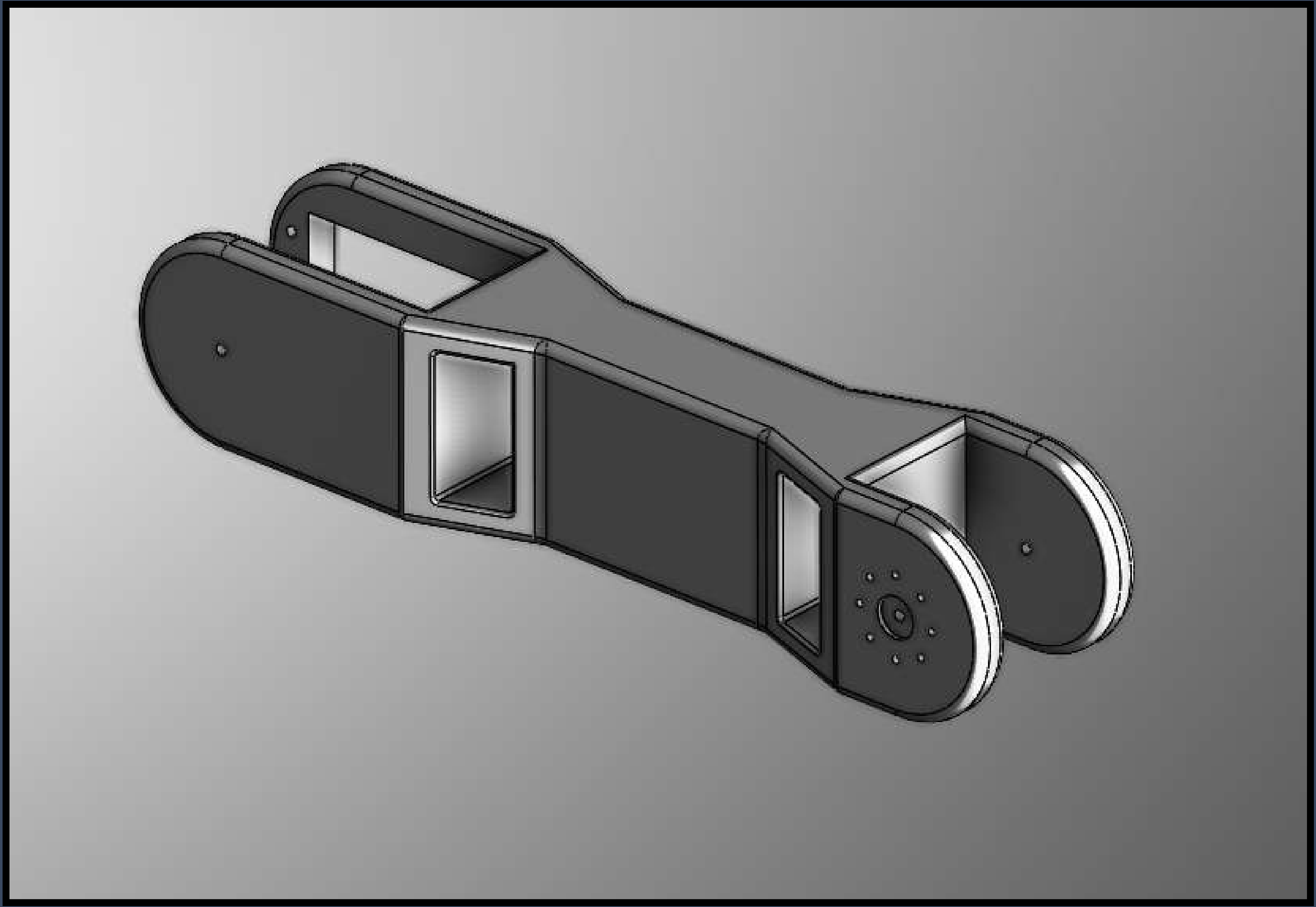
TOPOLOGY OPTIMIZATION FOR LINK 2

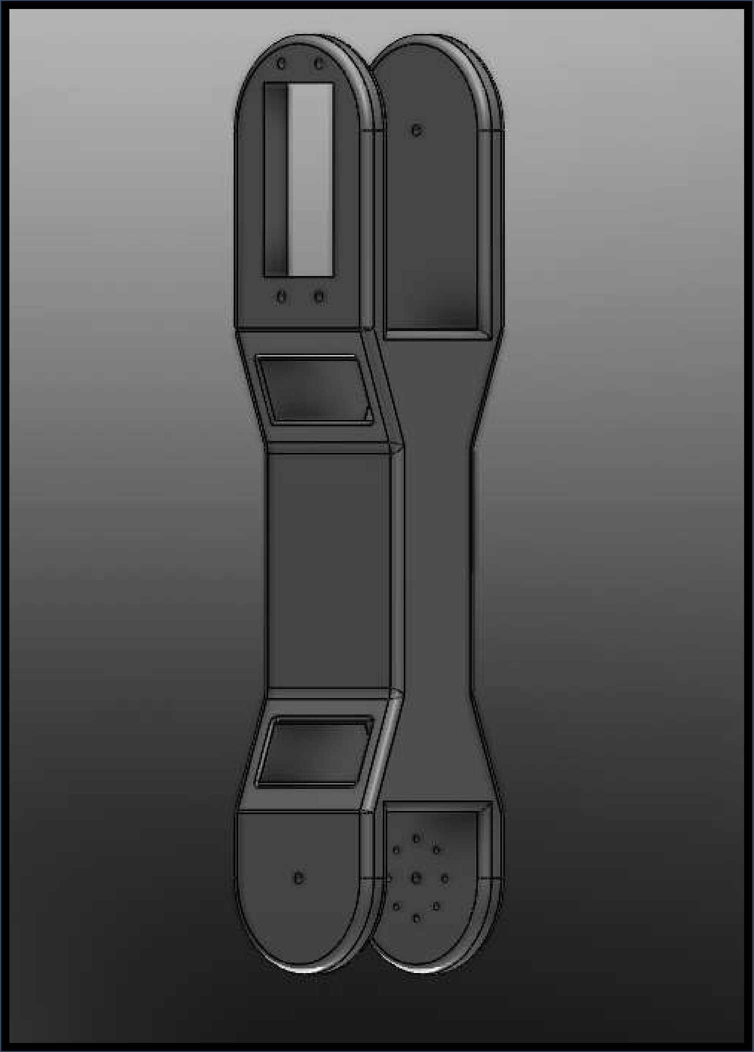




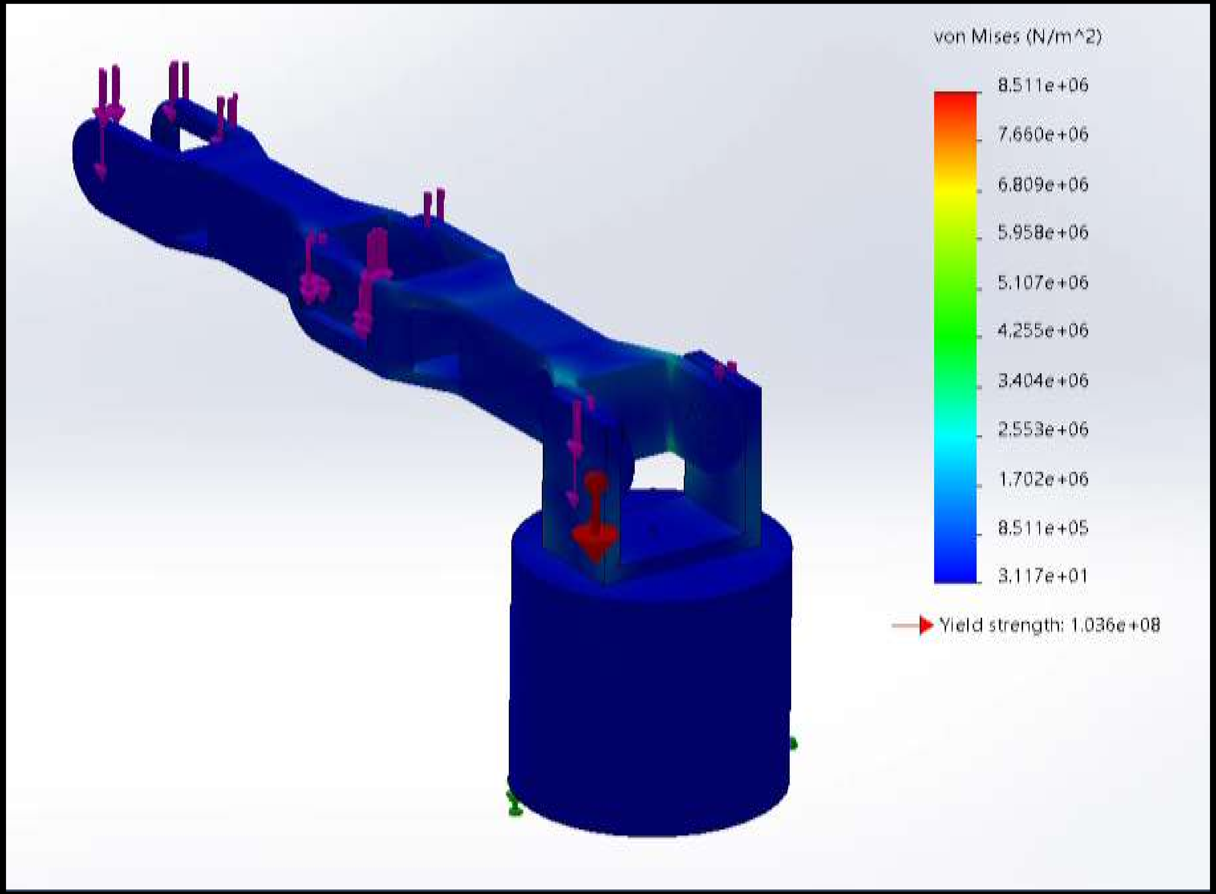


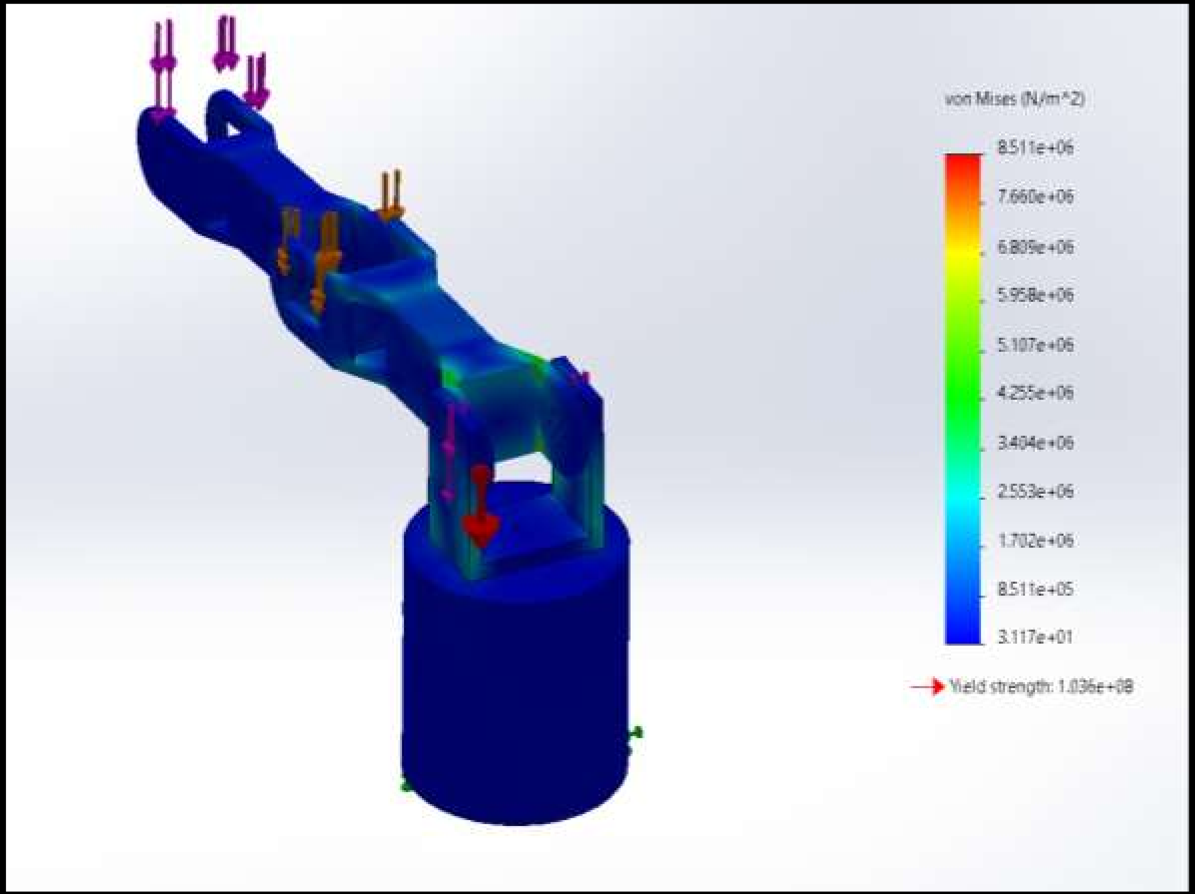
OPTIMIZED DESIGN FOR LINK 3



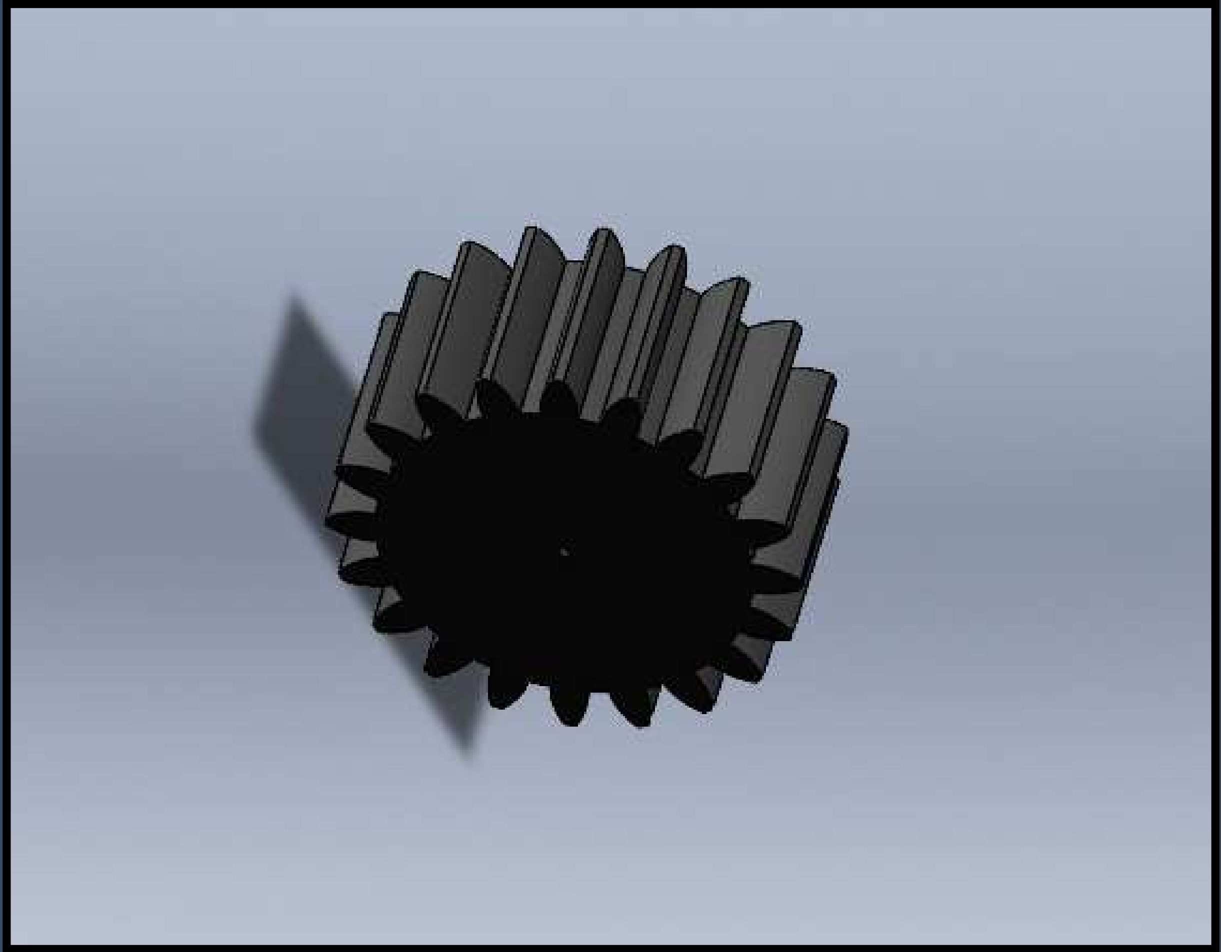


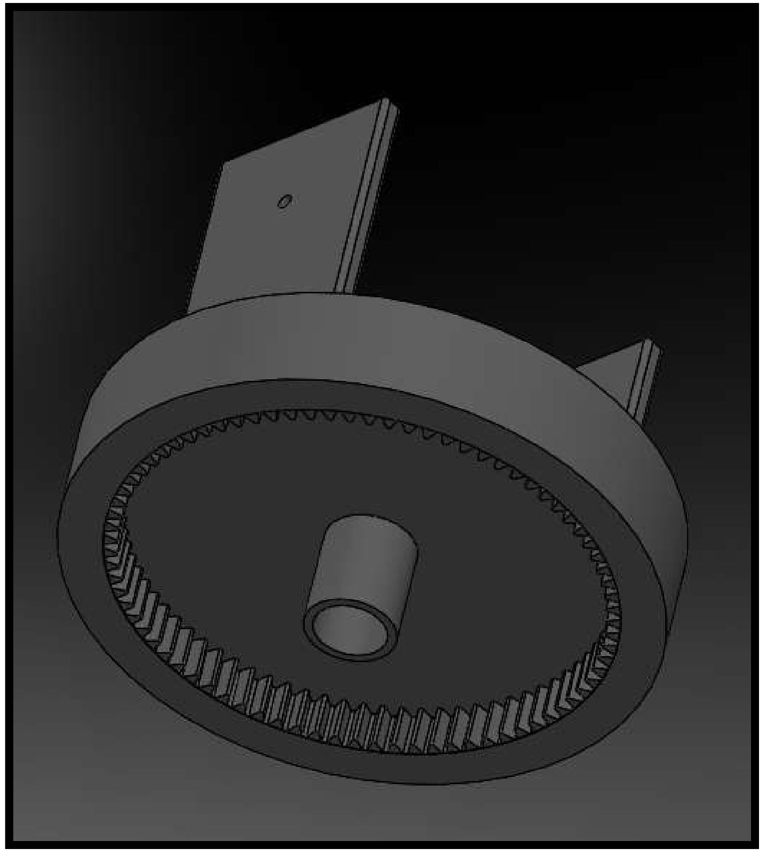
UPDATED STRESS DISTRIBUTION

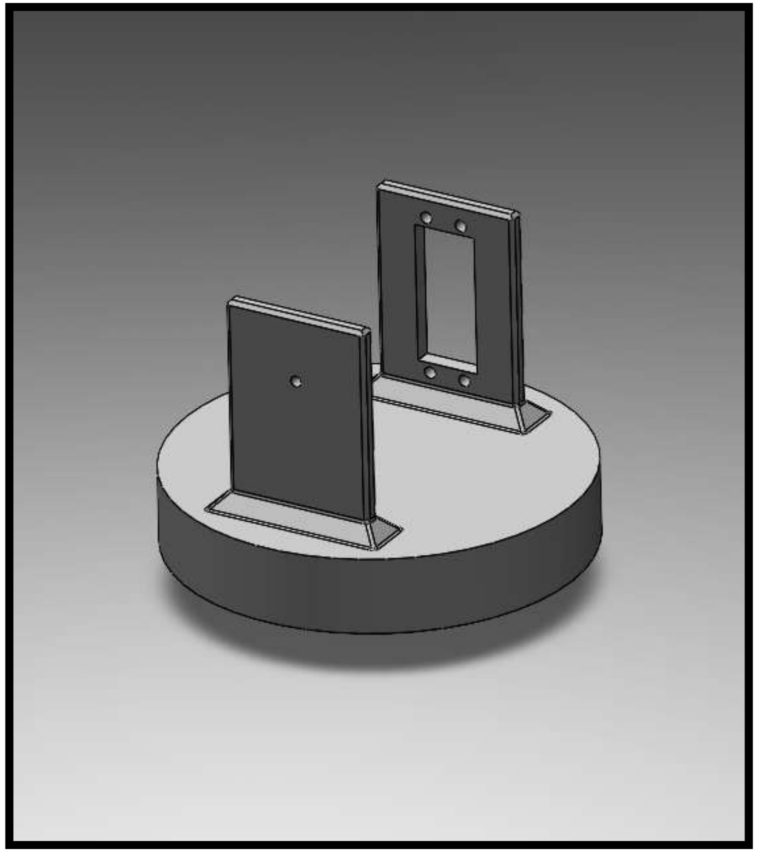




ROTATIONAL BASE DESIGN – GEARS

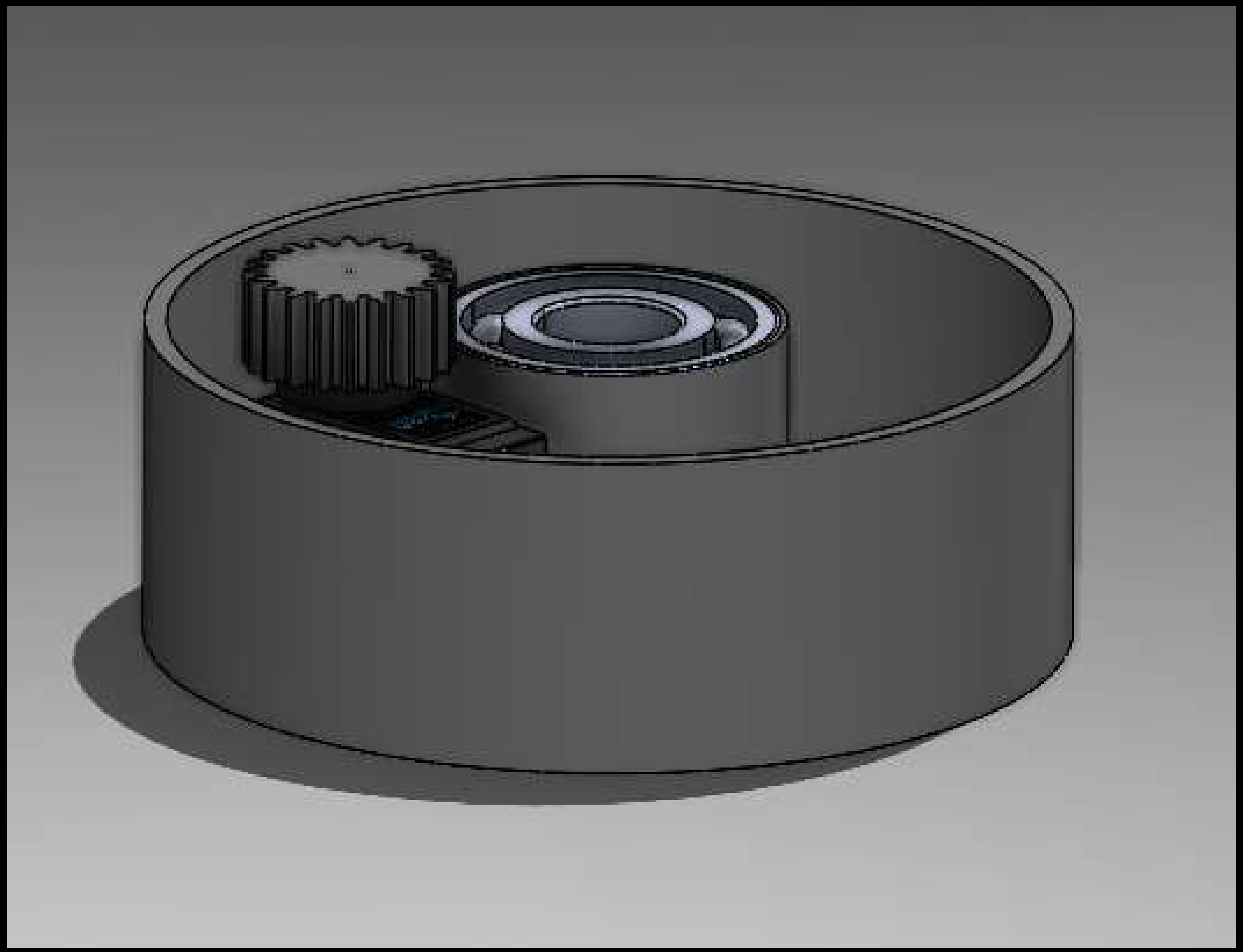




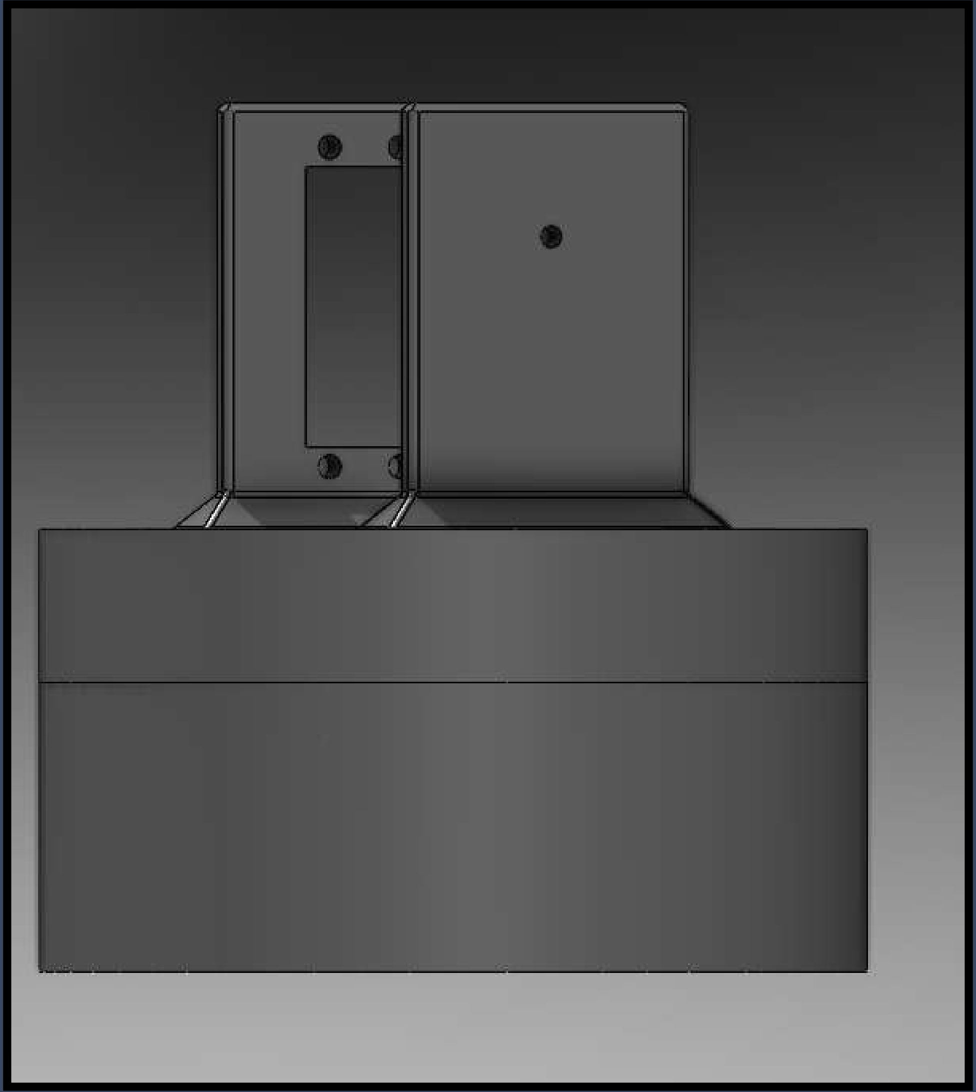


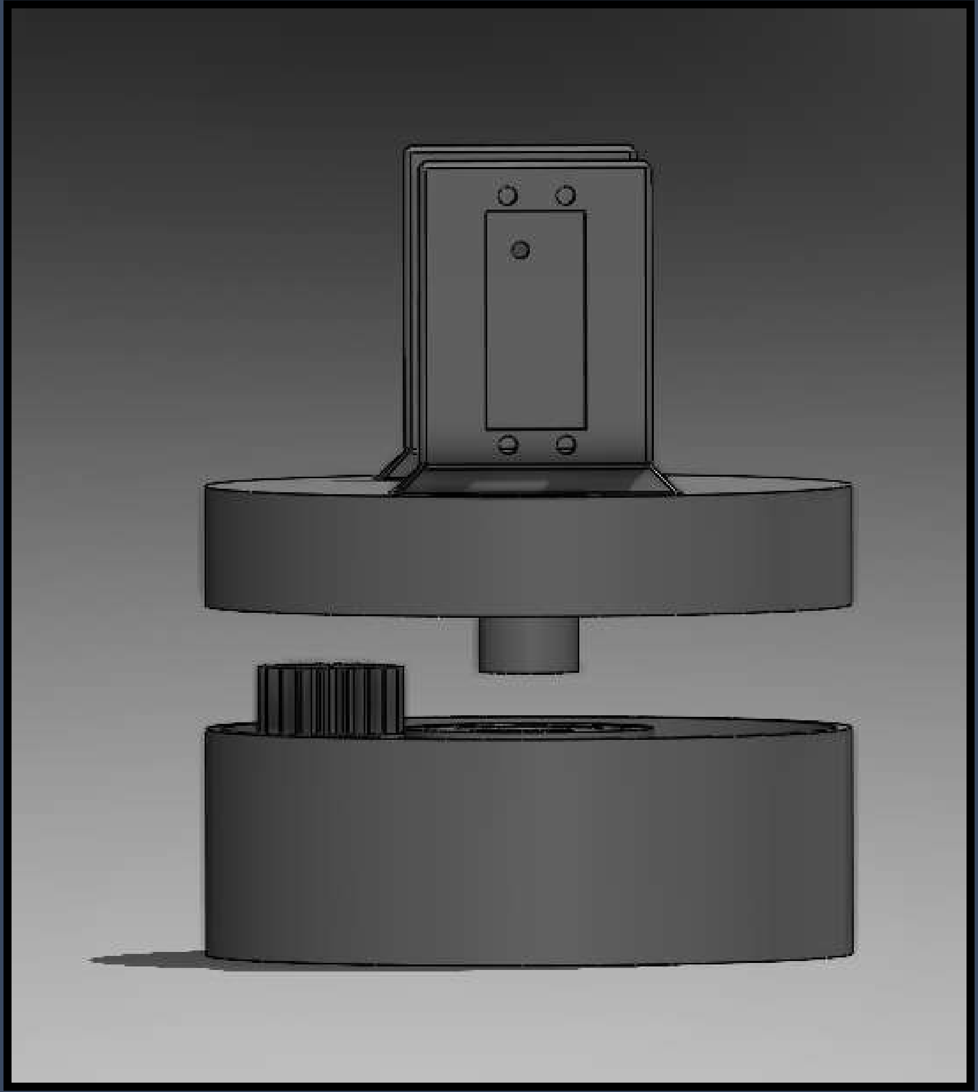
ROTATIONAL BASE DESIGN – TOP

ROTATIONAL BASE DESIGN – BOTTOM

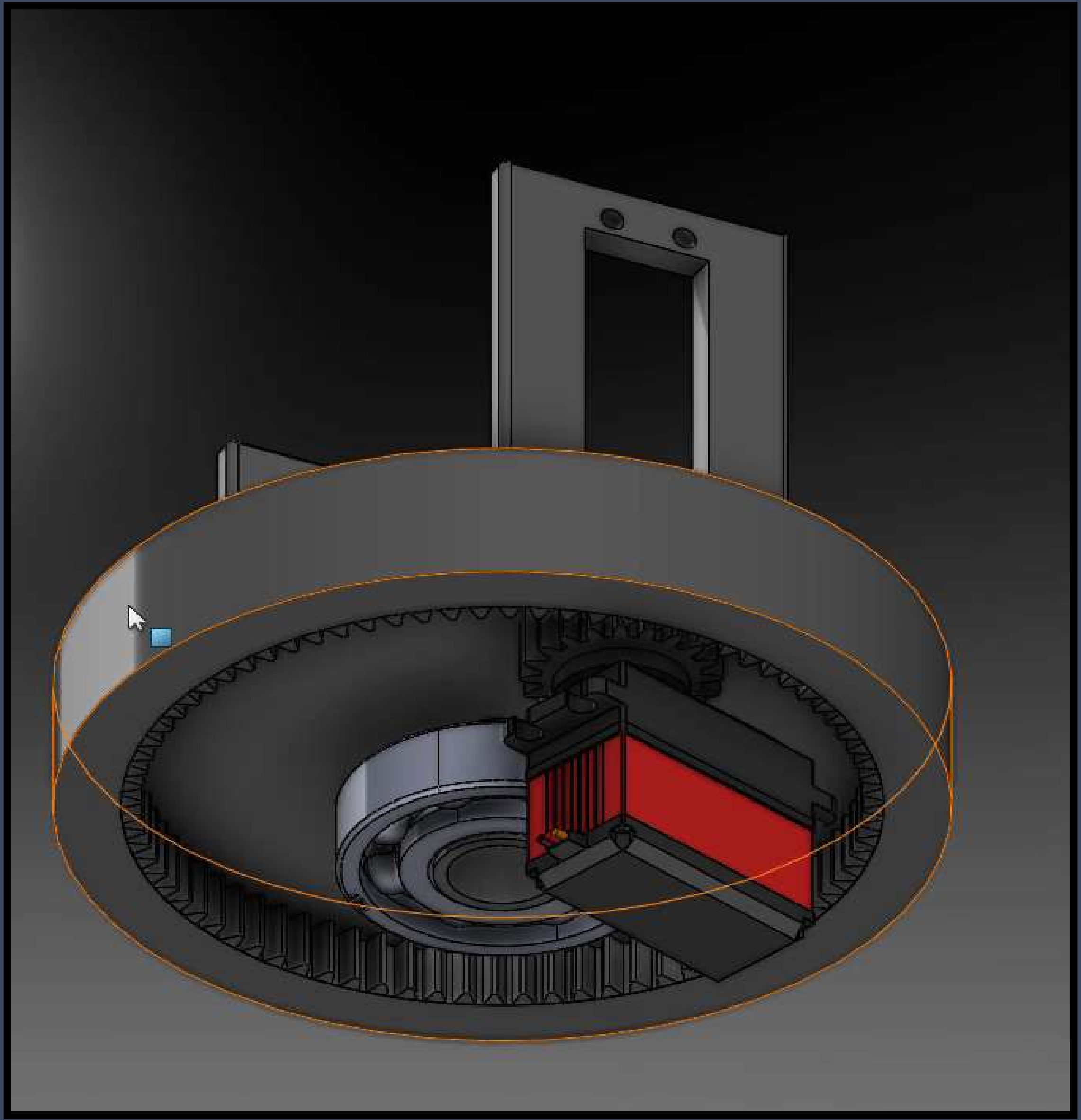


ROTATIONAL BASE DESIGN – COMPLETE

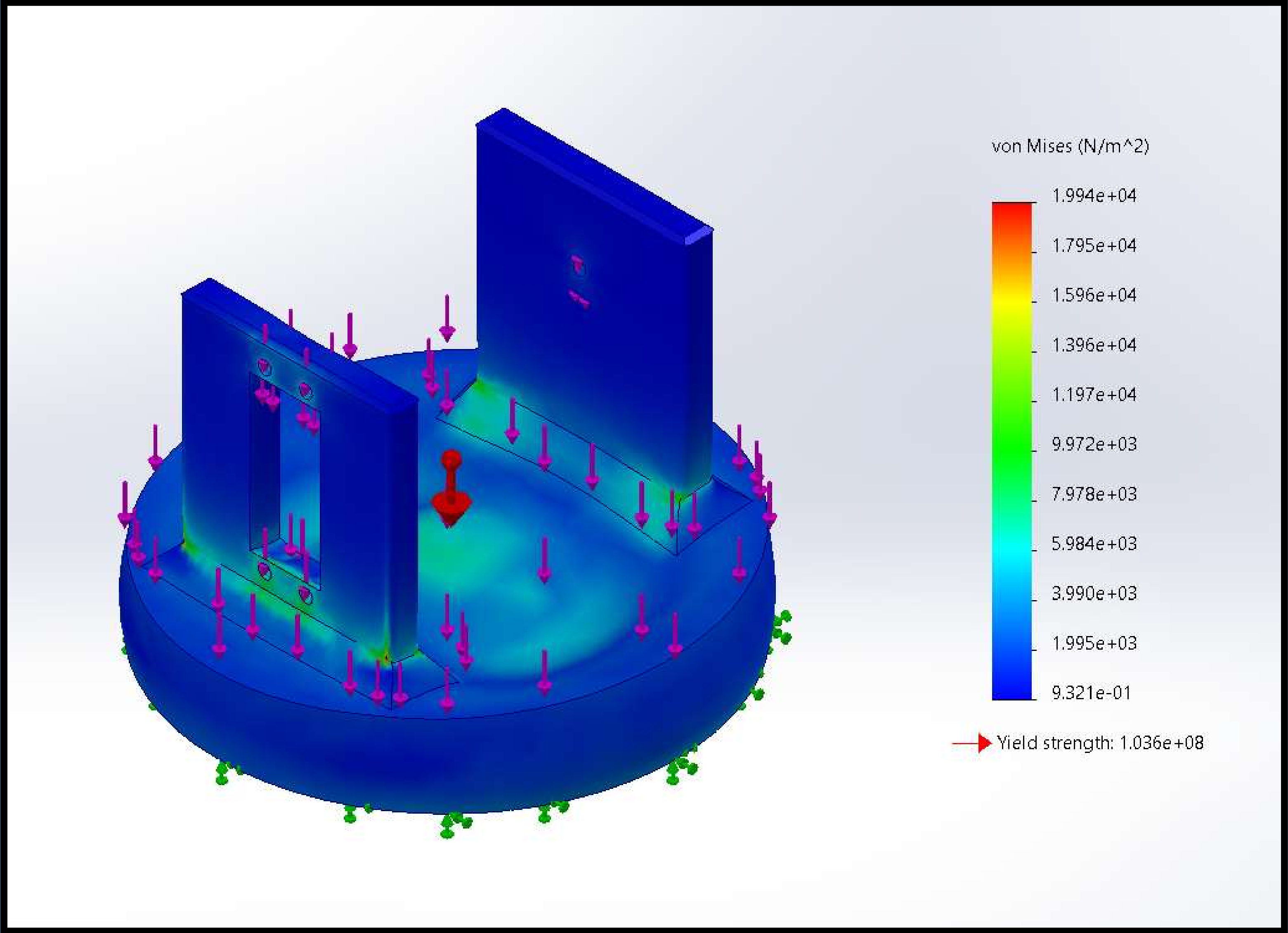




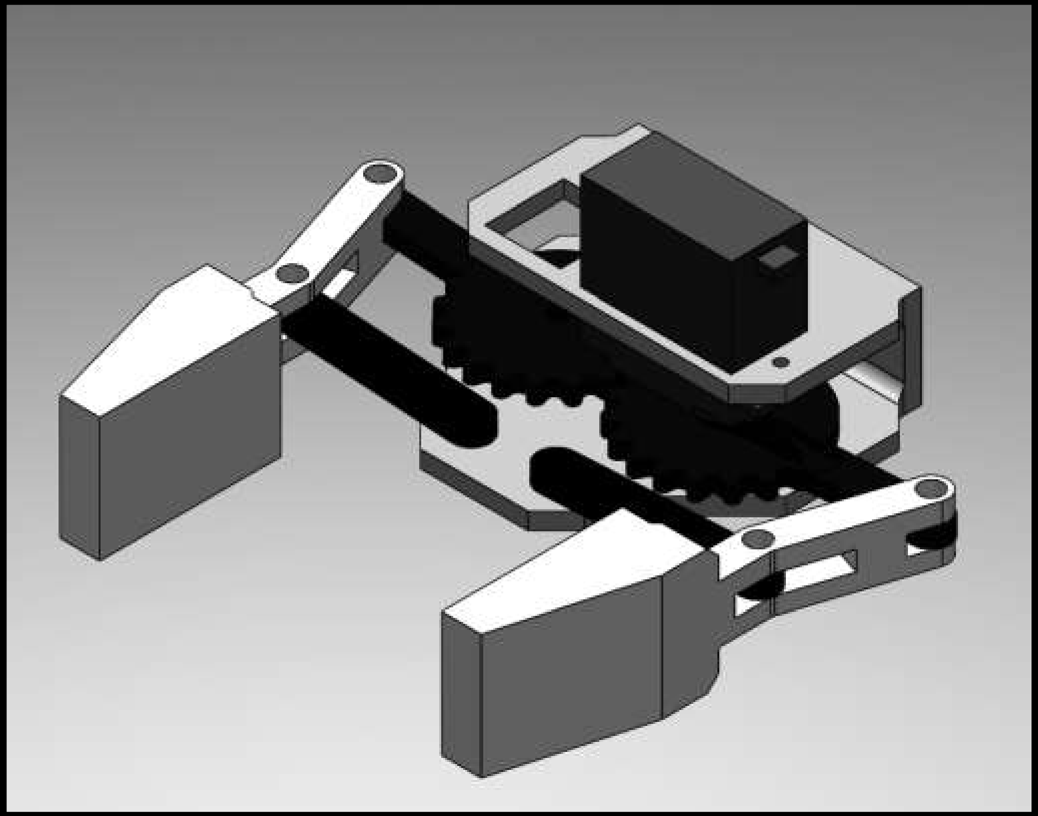
ROTATIONAL BASE DESIGN – MECHANISM

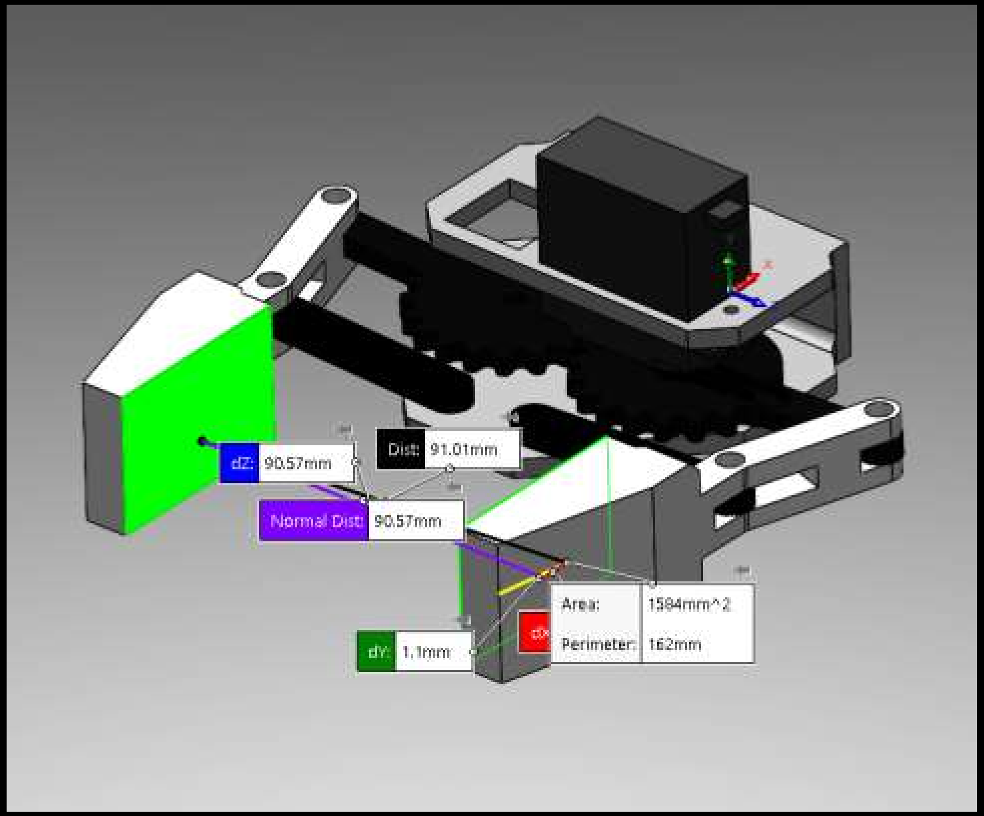


ROTATIONAL BASE DESIGN – STRESS DISTRIBUTION

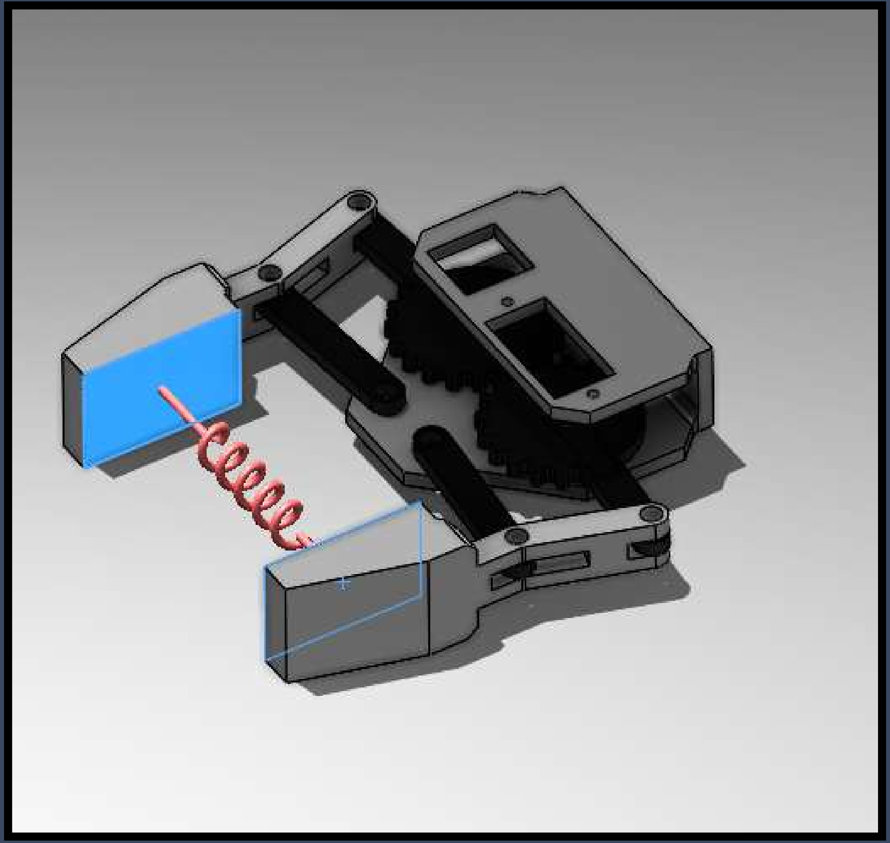


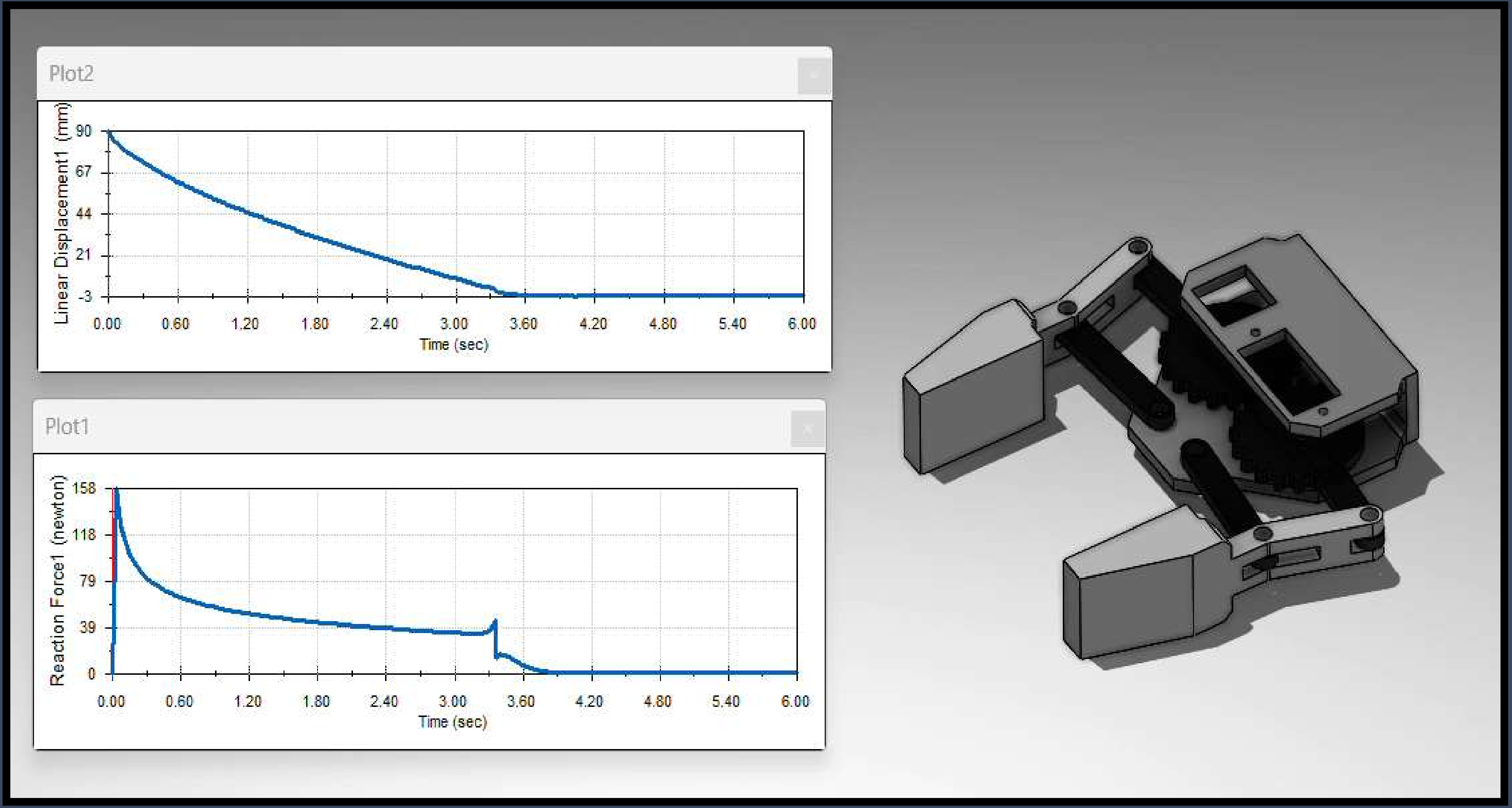
SOLIDWORK DESIGNS – GRIPPER





GRIPPING FORCE ESTIMATION



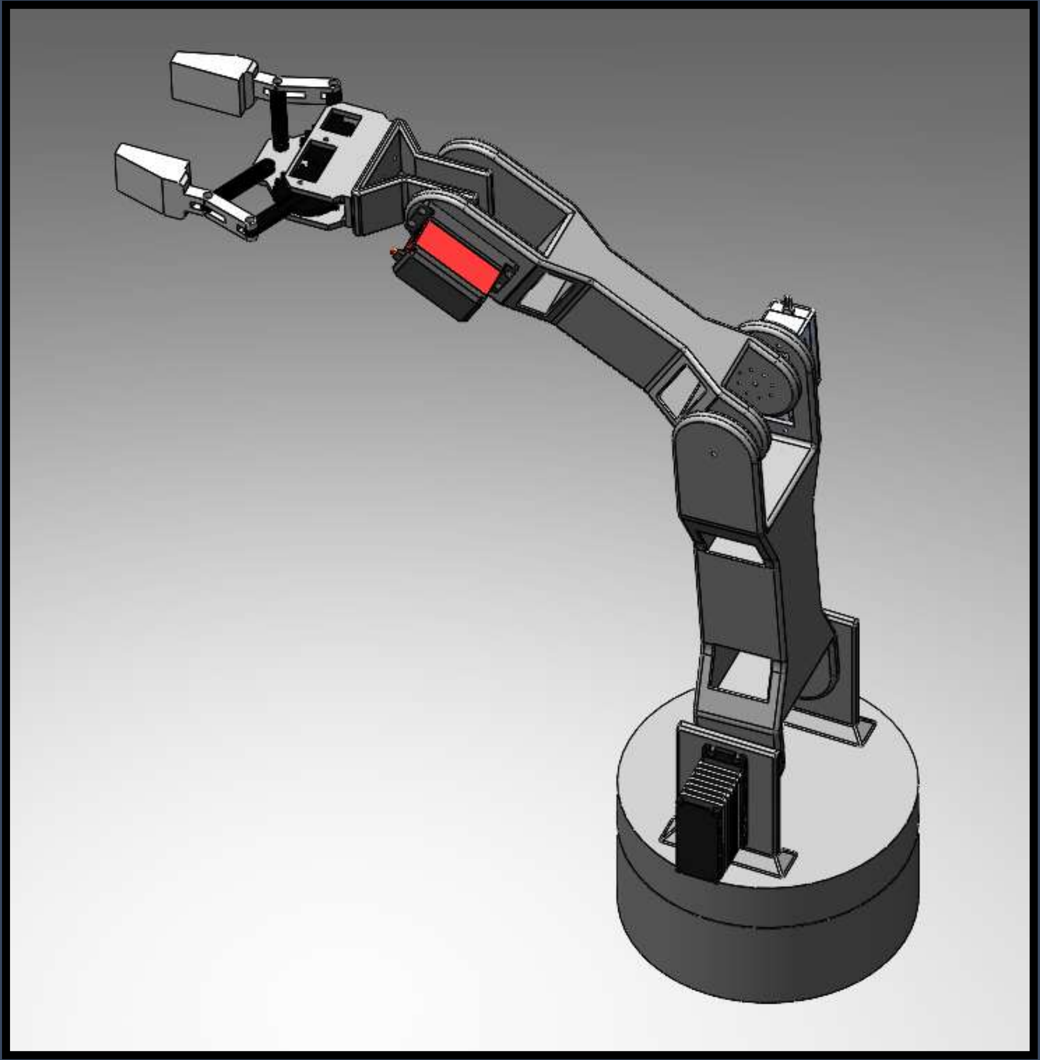


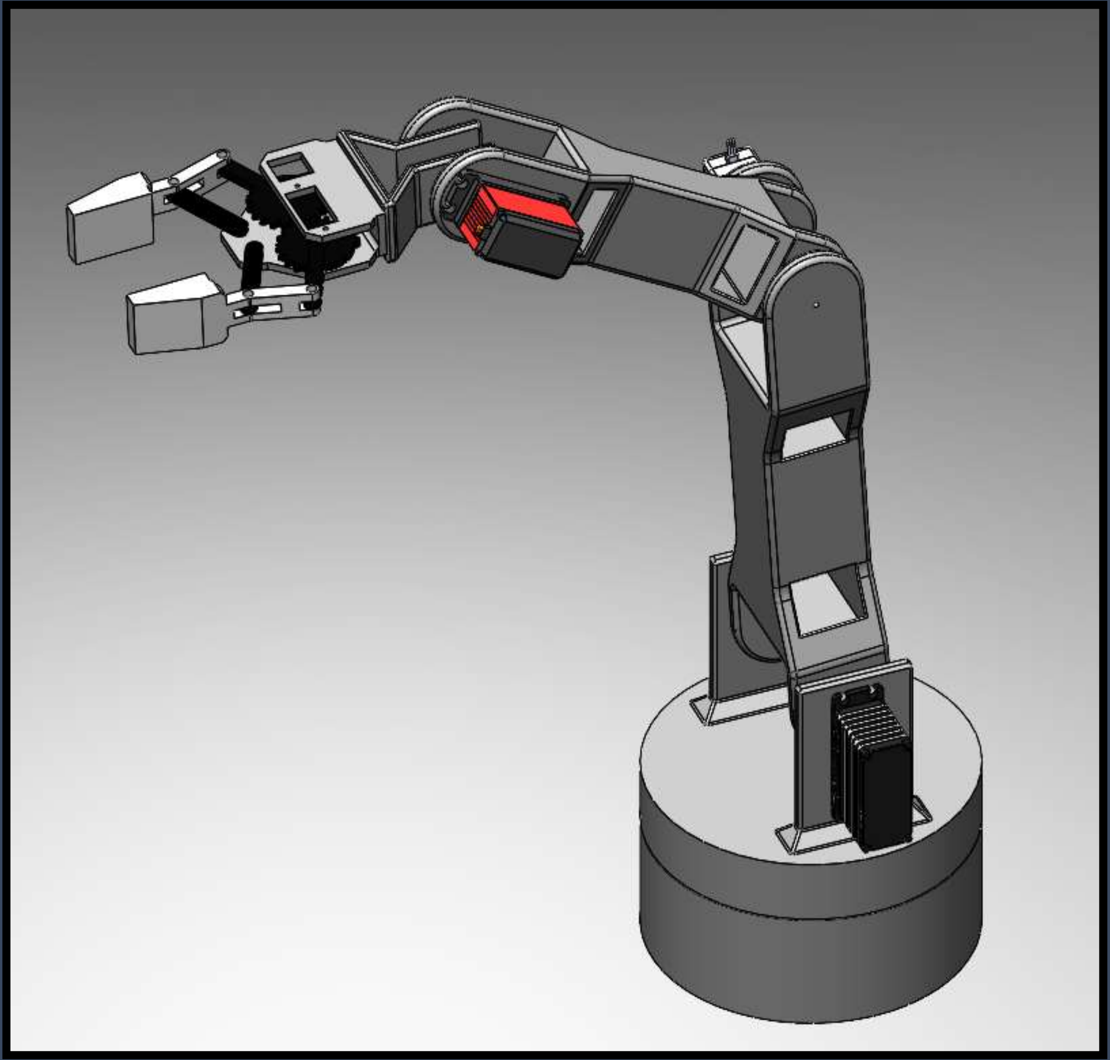
- ❑ Used motor torque = 10 kgcm
- ❑ Gripping Force = 39N
- ❑ Obtained Vertical Force on the Object = $39 \times 0.4 \times 2 = 31.2N$ $(Assumed\ the\ fricetion\ coeffient\ of\ material\ as\ 0.4)$
- ❑ Justification = 20N < 31.2N → 10 kgcm motor is enough.

MOTOR SELECTION – GRIPPER

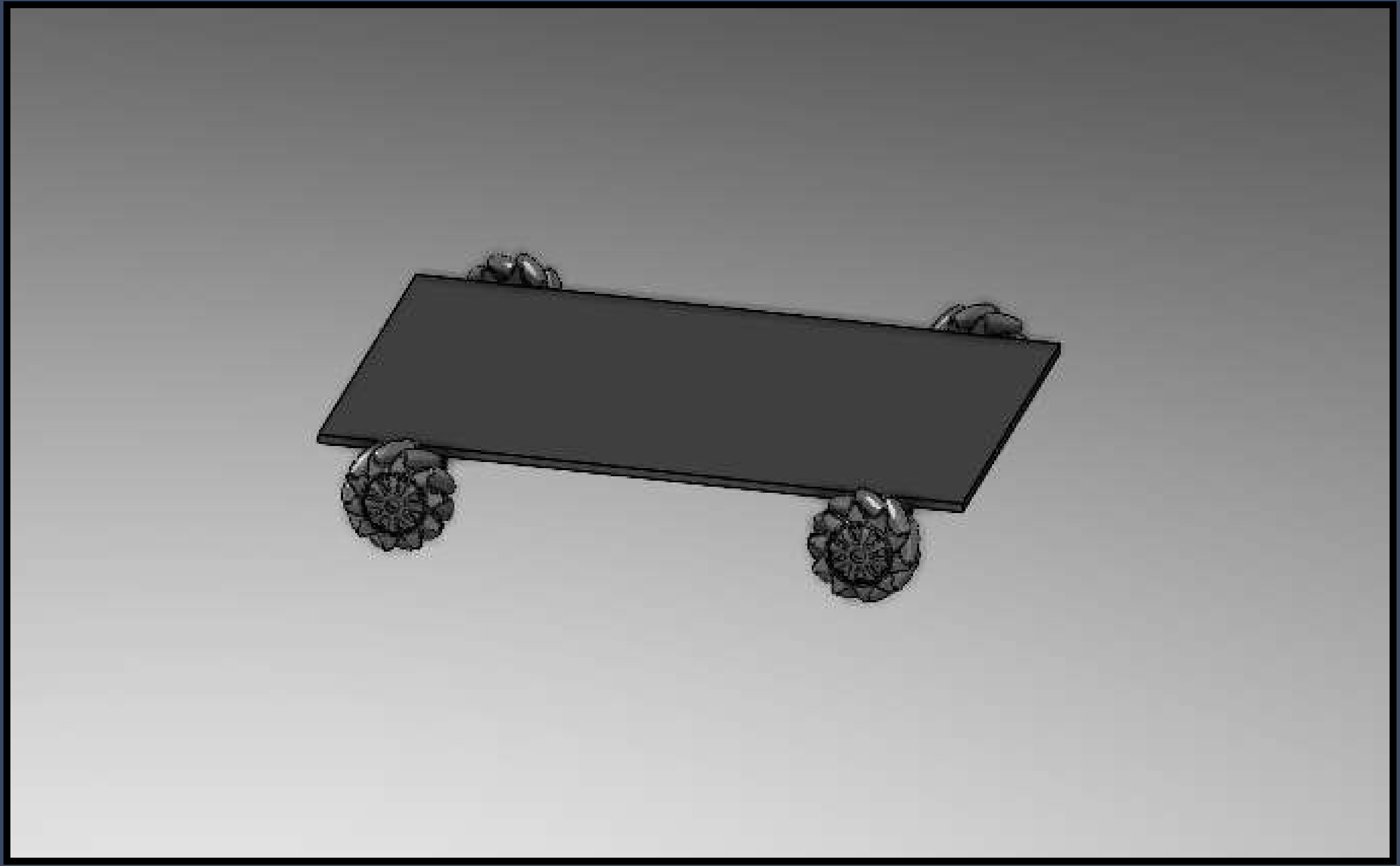
Selected Motor: SURPASS S1500M

UPDATED ROBOT ARM





MOBILE PLATFORM DESIGN- INITIAL MODEL



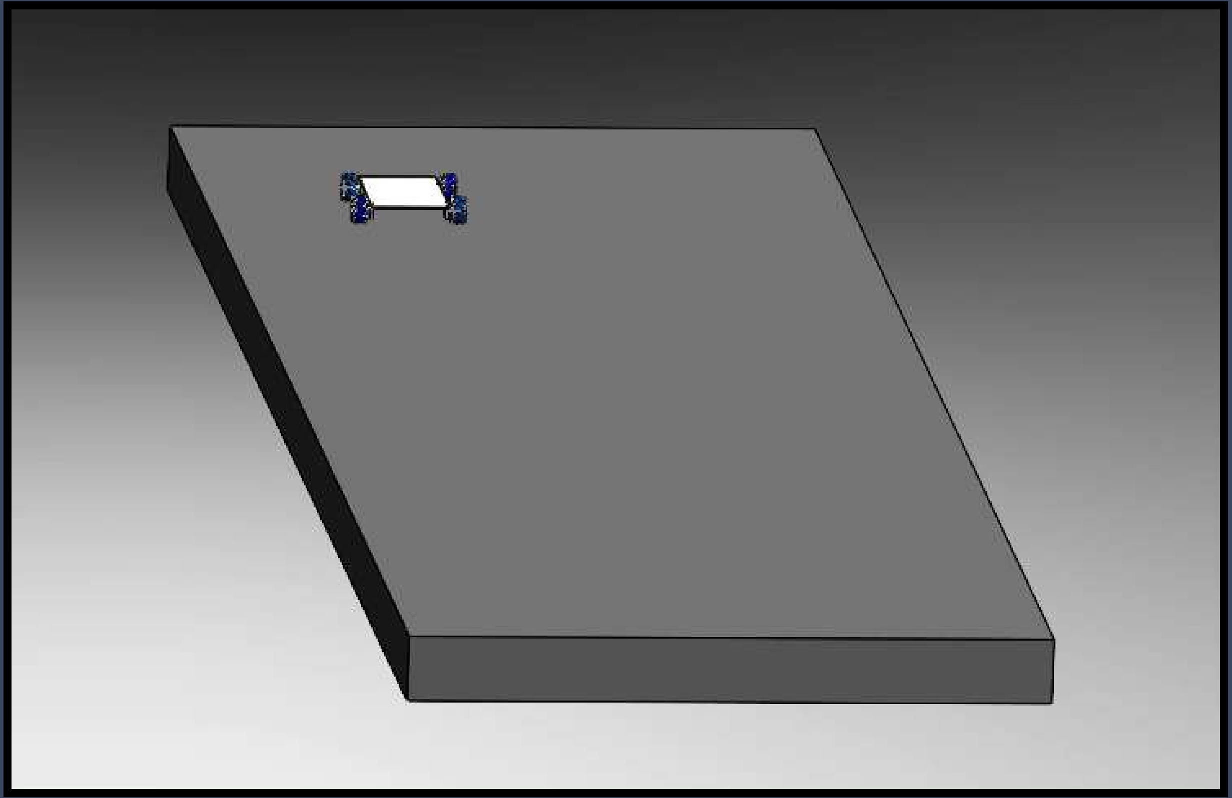
MATERIAL SELECTION – CHASSIS

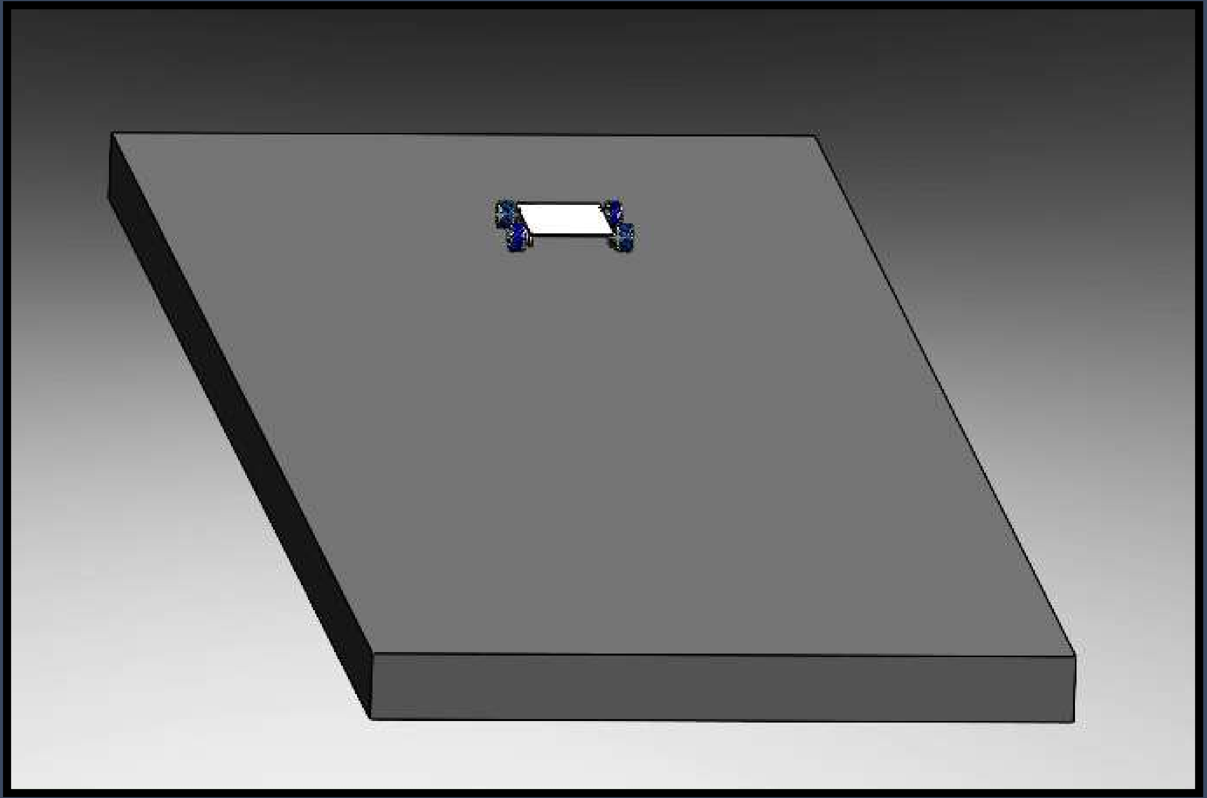
CHOSEN MATERIAL – ALUMINIUM 6061

- ❑ Lightweight: Offers a strong yet lightweight structure, enhancing mobility and efficiency.
- ❑ High Strength: Provides good mechanical strength, suitable for supporting the robot's components.
- ❑ Corrosion Resistance: Naturally resistant to corrosion, making it durable in various environments.
- ❑ Machinability: Easy to work with, allowing for precise cutting and shaping during fabrication.

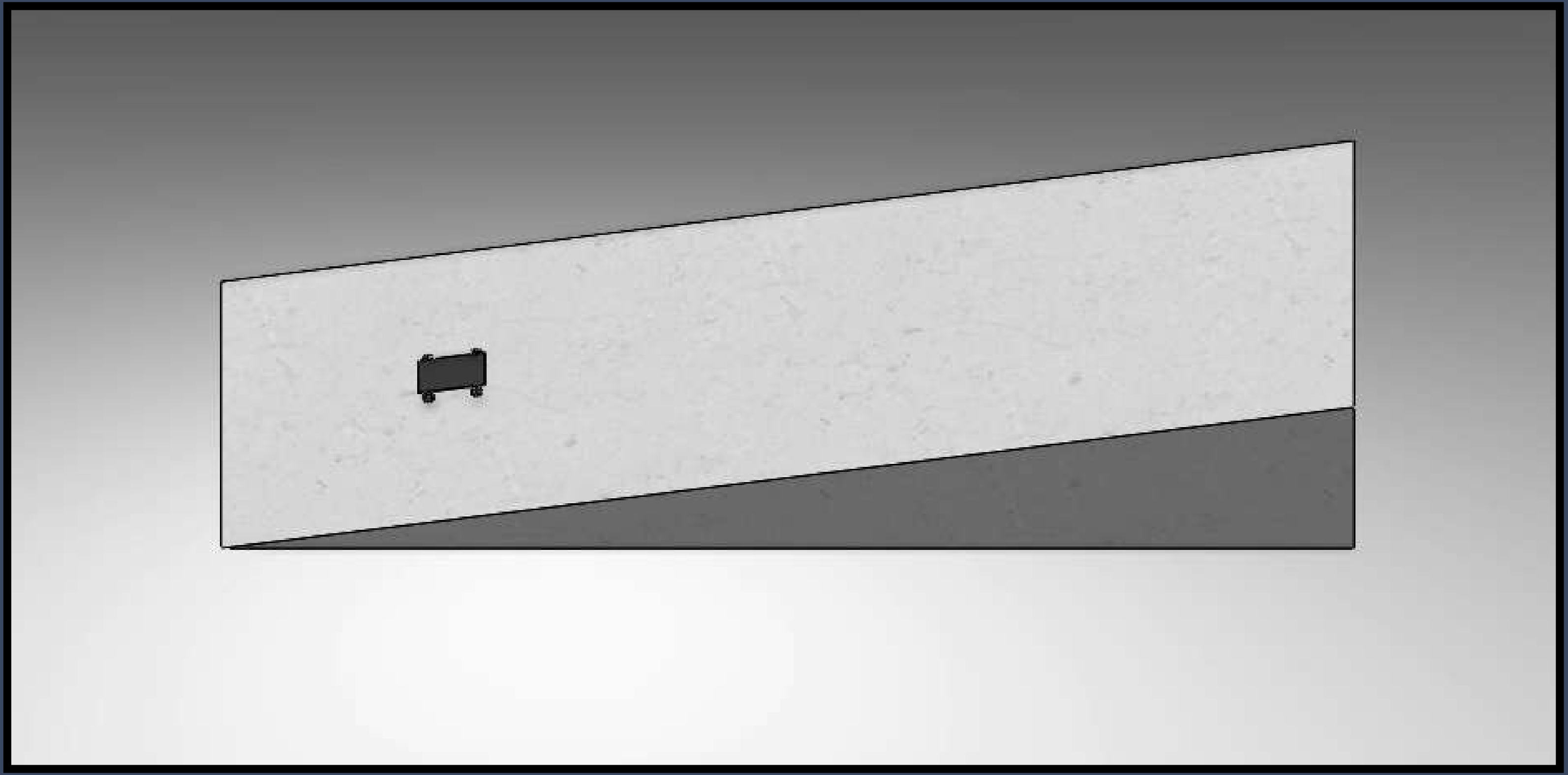
Physical Properties	Metric	English	Comments
Density	2.7 g/cc	0.0975 lb/in³	AA; Typical
Mechanical Properties			
Hardness, Brinell	95	95	AA; Typical; 500 g load; 10 mm ball
Hardness, Knoop	120	120	Converted from Brinell Hardness Value
Hardness, Rockwell A	40	40	Converted from Brinell Hardness Value
Hardness, Rockwell B	60	60	Converted from Brinell Hardness Value
Hardness, Vickers	107	107	Converted from Brinell Hardness Value
Ultimate Tensile Strength	310 MPa	45000 psi	AA; Typical
Tensile Yield Strength	276 MPa	40000 psi	AA; Typical
Elongation at Break	12 %	12 %	AA; Typical; 1/16 in. (1.6 mm) Thickness
Elongation at Break	17 %	17 %	AA; Typical; 1/2 in. (12.7 mm) Diameter
Modulus of Elasticity	68.9 GPa	10000 ksi	AA; Typical; Average of tension and compression. Compression modulus is about 2% greater than tensile modulus.
Notched Tensile Strength	324 MPa	47000 psi	2.5 cm width x 0.16 cm thick side-notched specimen, K_t = 17.
Ultimate Bearing Strength	607 MPa	88000 psi	Edge distance/pin diameter = 2.0
Bearing Yield Strength	386 MPa	56000 psi	Edge distance/pin diameter = 2.0
Poisson's Ratio	0.33	0.33	Estimated from trends in similar Al alloys.
Fatigue Strength	96.5 MPa	14000 psi	AA; 500,000,000 cycles completely reversed stress; RR Moore machine/specimen
Fracture Toughness	29 MPa-m½	26.4 ksi-in½	K_{IC}; TL orientation.
Machinability	50 %	50 %	0-100 Scale of Aluminum Alloys
Shear Modulus	26 GPa	3770 ksi	Estimated from similar Al alloys.
Shear Strength	207 MPa	30000 psi	AA; Typical
Electrical Properties			
Electrical Resistivity	3.99e-006 ohm-cm	3.99e-006 ohm-cm	AA; Typical at 68°F
Thermal Properties			
CTE, linear 68°F	23.6 µm/m-°C	13.1 µin/in-°F	AA; Typical; Average over 68-212°F range.
CTE, linear 250°C	25.2 µm/m-°C	14 µin/in-°F	Estimated from trends in similar Al alloys. 20-300°C.
Specific Heat Capacity	0.896 J/g-°C	0.214 BTU/lb-°F	
Thermal Conductivity	167 W/m-K	1160 BTU-in/hr-ft²-°F	AA; Typical at 77°F
Melting Point	582 - 652 °C	1080 - 1205 °F	AA; Typical range based on typical composition for wrought products 1/4 inch thickness or greater; Eutectic melting can be completely eliminated by homogenization.
Solidus	582 °C	1080 °F	AA; Typical
Liquidus	652 °C	1205 °F	AA; Typical

MOBILE PLATFORM DESIGN- MOTOR TORQUE ESTIMATION ANALYSIS



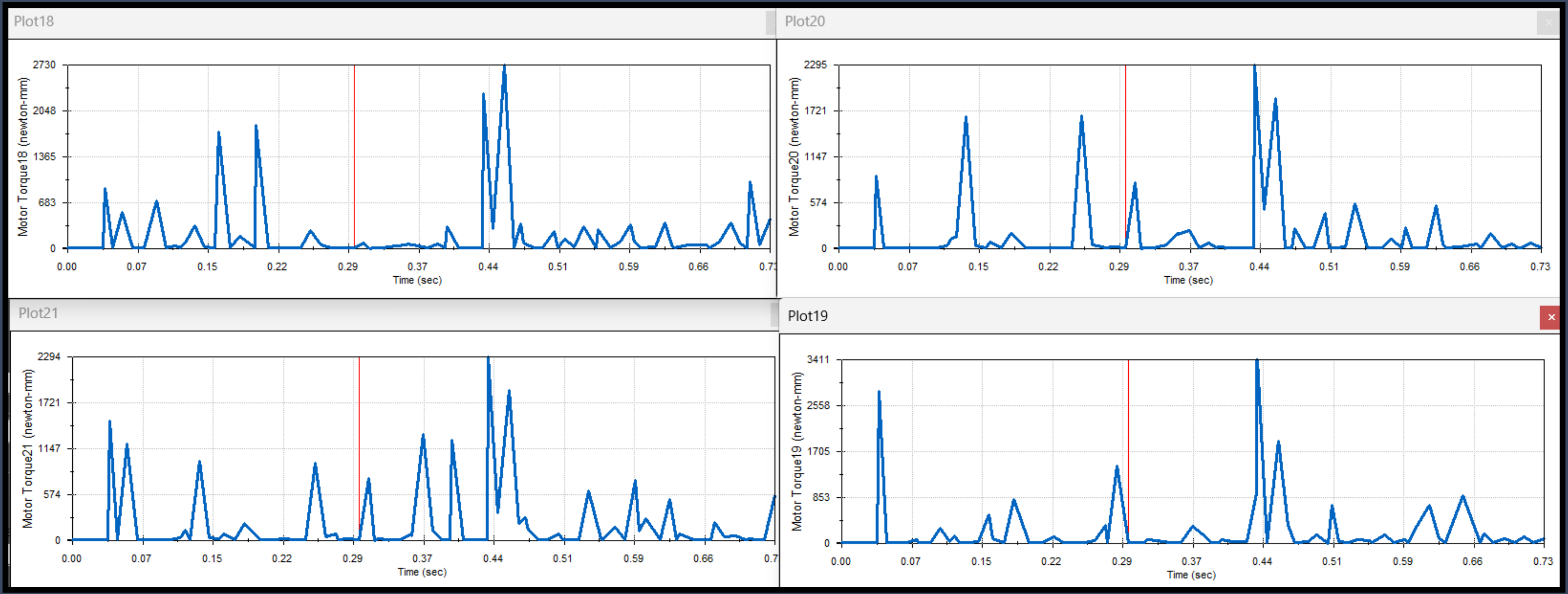


MOBILE PLATFORM DESIGN- MOTOR TORQUE ESTIMATION ANALYSIS



Slope – 10 Degrees
RPM – 100

MOBILE PLATFORM DESIGN- MOTOR TORQUE ESTIMATION



Motor Torque Required per Wheel – 25kgcm

Brand	CHIHAI MOTOR
Model	CHR-GM37-3429 DC Photoelectric coding motor
Shaft Length	21mm
Shaft Diameter	6mm D
Voltage	DC 6V-24V
Wiring specification	PH2.0-6PIN (Standard connection cable output DuPont or XH2.54 head)
Basic pulse number	448CPR
Weight	About 200g

Model: CHR-GM37-3429S DC Photoelectric coding motor

Voltage: DC 24.0V max power 11W

Reduction ratio	1: 6.3	1: 10	1:18.8	1: 30	1: 50	1: 90	1: 150	1: 270	1: 450
No-load current(mA)	≤150	≤150	≤150	≤150	≤150	≤150	≤150	≤150	≤150
No-load speed(rpm)	1650	1000	530	330	200	110	65	36	22
Rated torque(Kg.cm)	1.0	1.6	3.0	4.8	8.0	14.0	24.0	30.0	30.0
Rated torque(N.m)	0.1	0.16	0.3	0.48	0.8	1.4	2.4	3	3
Rated speed(rpm)	950	600	320	200	120	65	40	27	16
Rated current(A)	≤1.8	≤1.8	≤1.8	≤1.8	≤1.8	≤1.8	≤1.8	≤1.8	≤1.8
Stall torque(kg.cm)	≥2.5	≥4.0	≥7.5	≥12	≥20	Can't exceed 30.0kg.cm(3.0N.m)			
Stall current(A)	≤4.5	≤4.5	≤4.5	≤4.5	≤4.5	≤4.5	≤4.5	≤4.5	≤4.5
Reducer length L(mm)	19.0	19.0	21.5	21.5	24.0	24.0	26.5	26.5	29.0

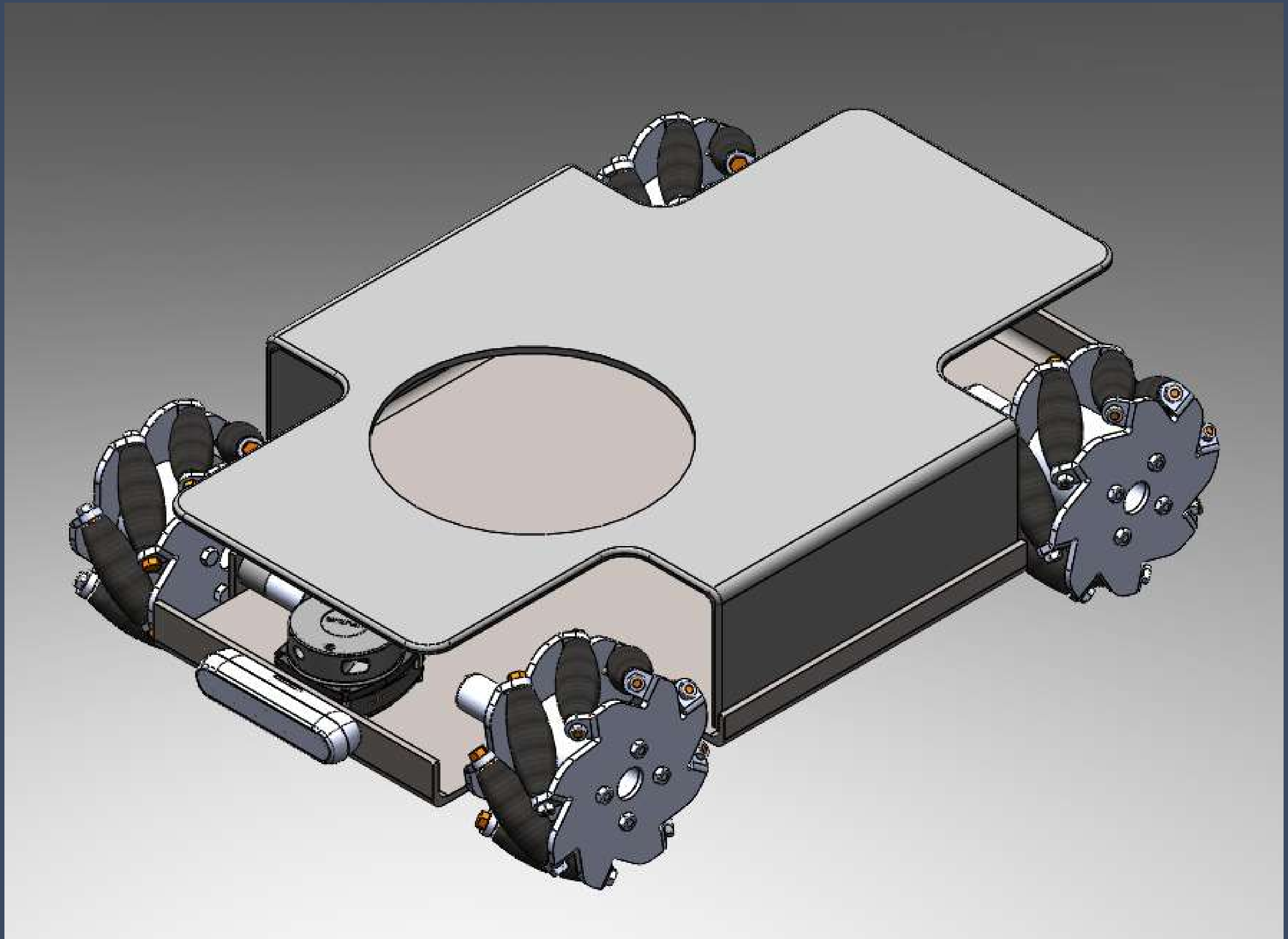
Voltage: DC 12.0V max power 11W

Reduction ratio	1: 6.3	1: 10	1:18.8	1: 30	1: 50	1: 90	1: 150	1: 270	1: 450
No-load current(mA)	≤300	≤300	≤300	≤300	≤300	≤300	≤300	≤300	≤300
No-load speed(rpm)	1650	1000	530	330	200	110	65	36	22
Rated torque(Kg.cm)	1.0	1.6	3.0	4.8	8.0	14.0	24.0	30.0	30.0
Rated torque(N.m)	0.1	0.16	0.3	0.48	0.8	1.4	2.4	3	3
Rated speed(rpm)	950	600	320	200	120	65	40	27	16
Rated current(A)	≤2.3	≤2.3	≤2.3	≤2.3	≤2.3	≤2.3	≤2.1	≤1.9	≤1.7
Stall torque(kg.cm)	≥2.5	≥4.0	≥7.5	≥12	≥20	Can't exceed 30.0kg.cm(3.0N.m)			

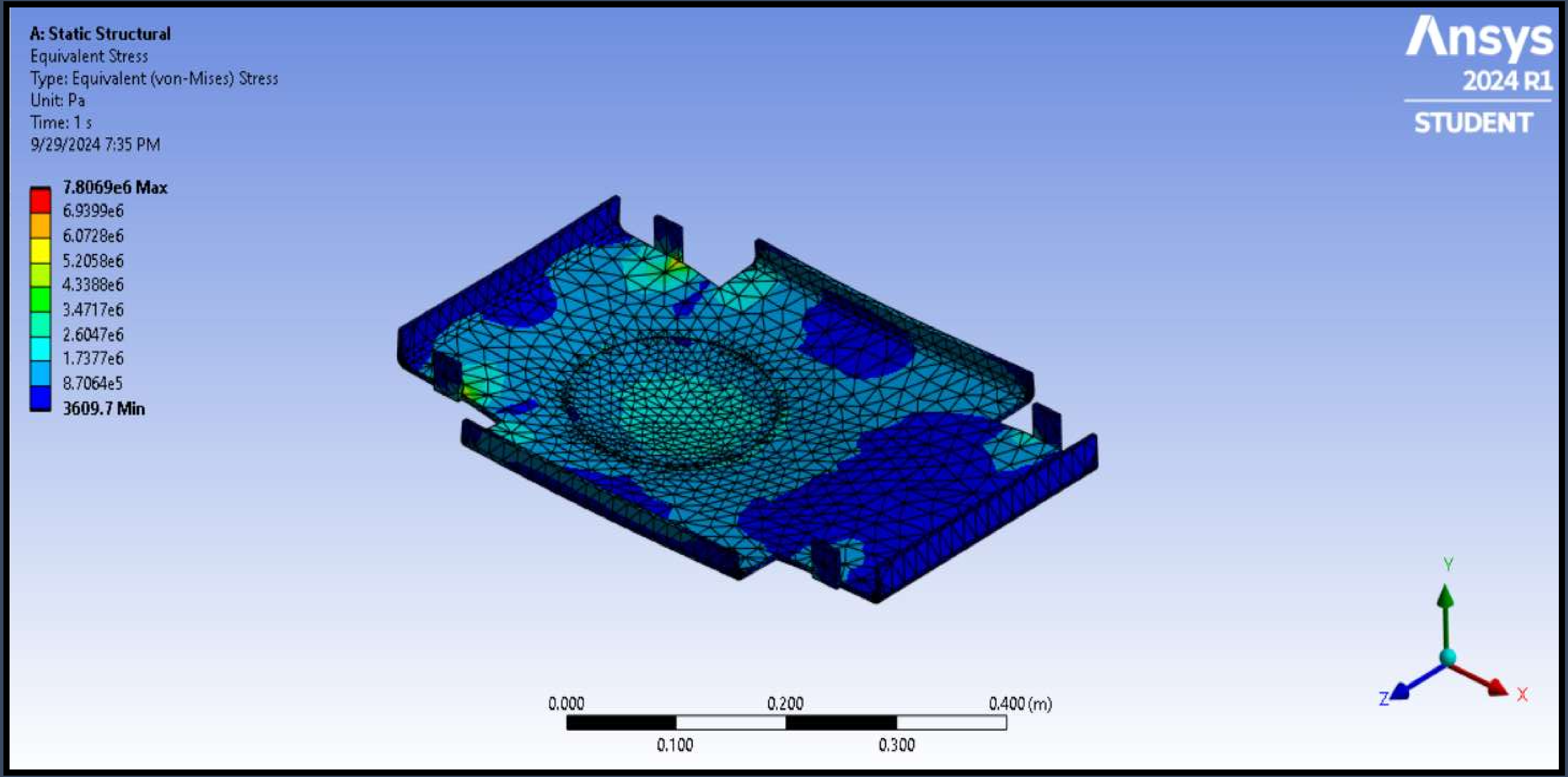
MOBILE PLATFORM DESIGN– MOTOR TORQUE ESTIMATION

SELECTED MOTOR: CHR-GM37-3429E

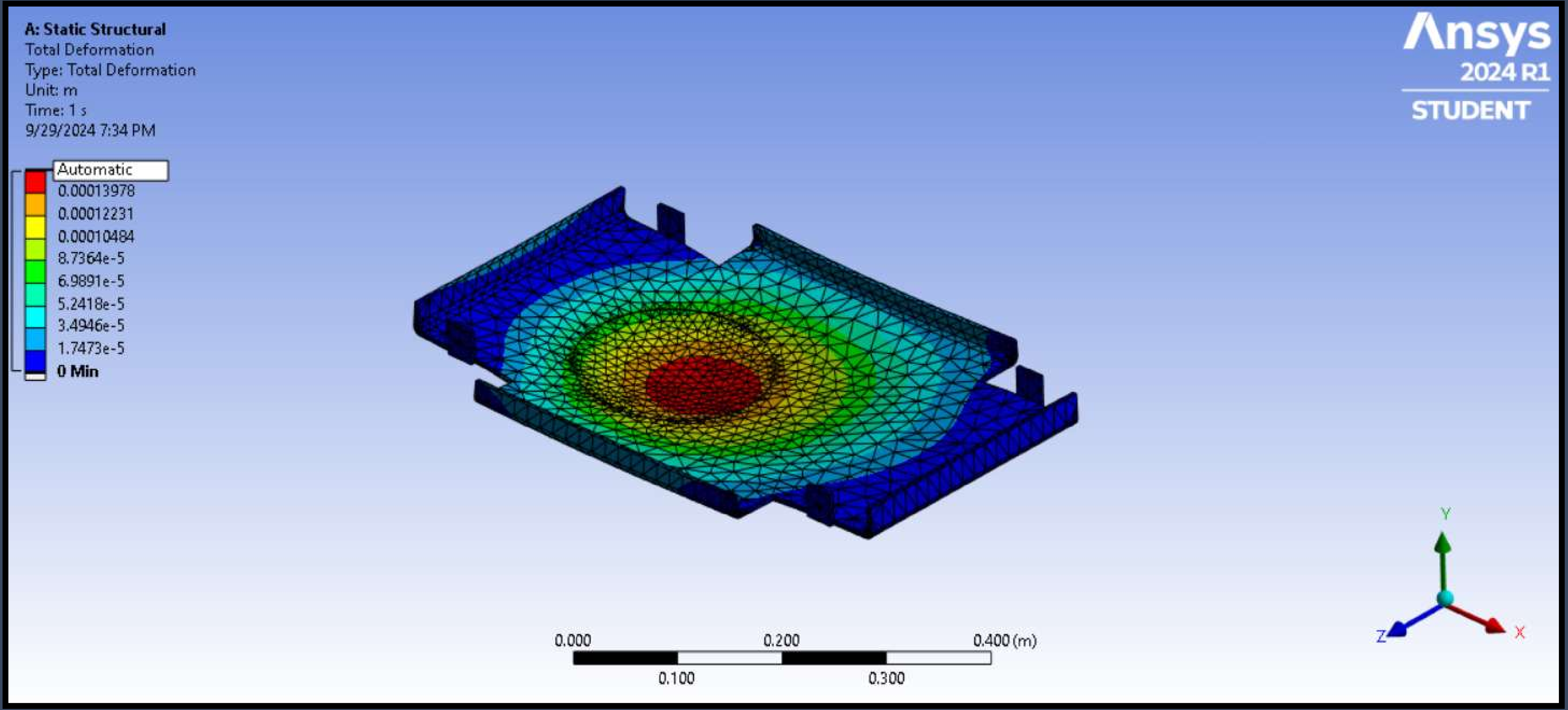
UPDATED MOBILE PLATFORM DESIGN



STRESS DISTRIBUTION

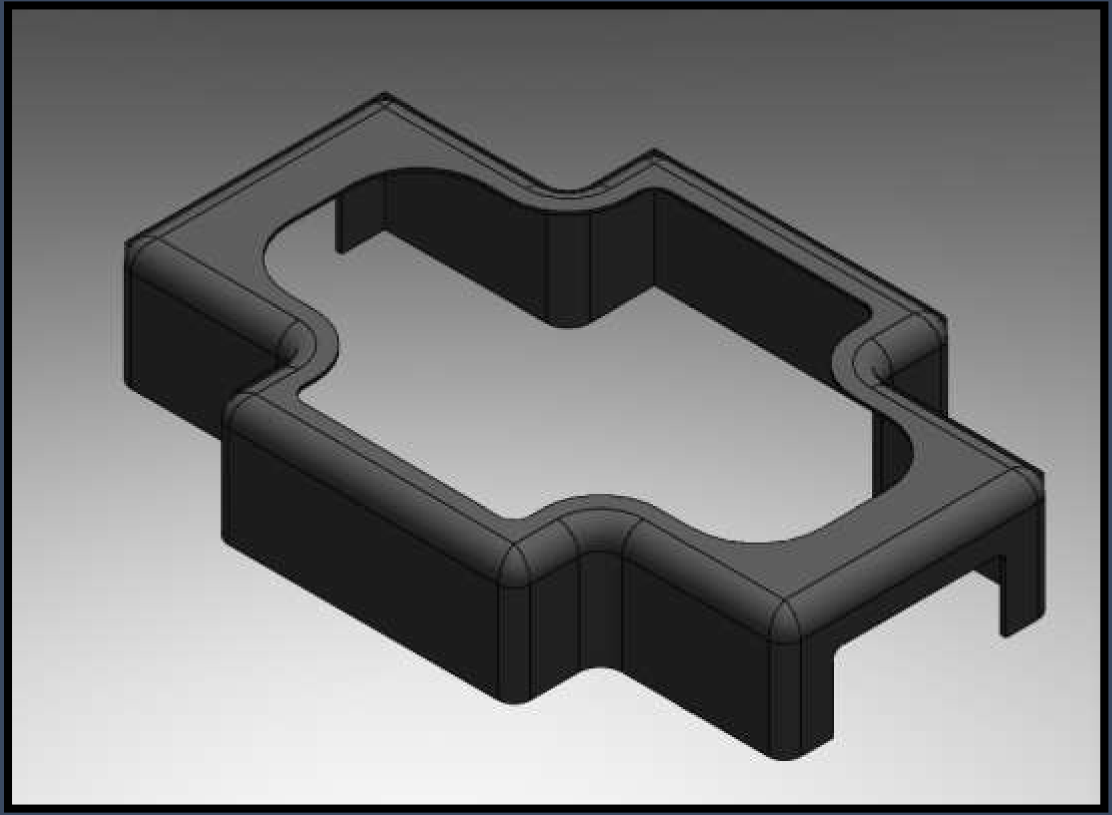


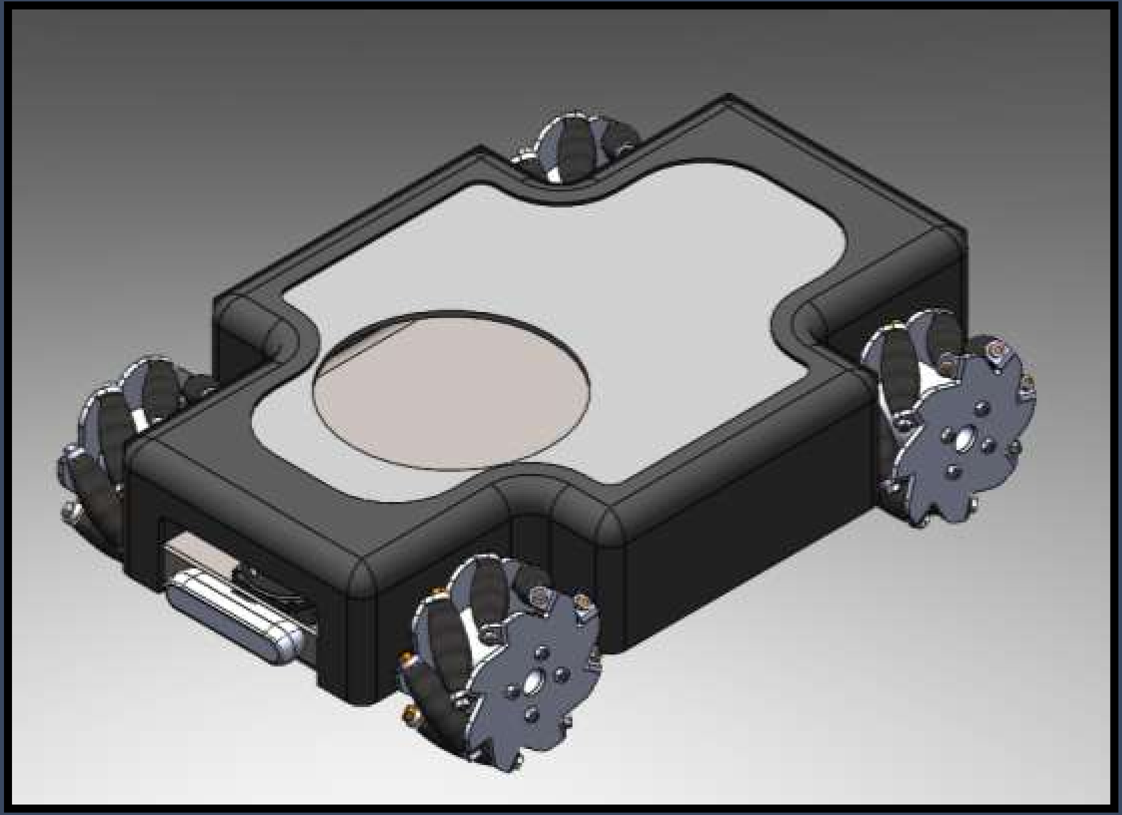
DEFORMATION OF THE CHASSIS PLATE



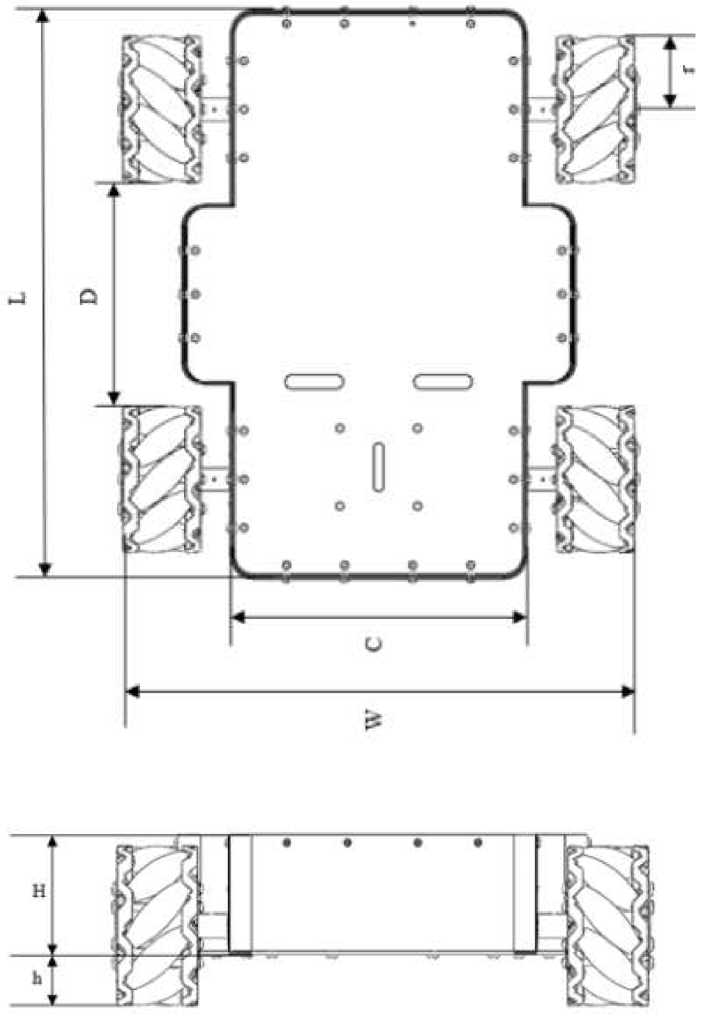
Maximum Deflection: 0.17mm

UPDATED MOBILE PLATFORM DESIGN





DIMENSIONS OF THE CHASSIS



Symbol	Explanation	Value
L	Length of the Chassis	600mm
W	Width of the Chassis	420mm
C	Distance between right and left wheel	240mm
D	Distance between front and back wheel	300mm
r	Radius of the wheel	150mm
H	Chassis height	113mm
h	Ground Clearance	50mm

STABILITY ANALYSIS & OPTIMAL MOUNTING LOCATION

•**Importance**: Optimal arm placement ensures system stability, efficiency, and safety, reducing risks like tipping and operational inefficiencies.

•**Simulation**: MATLAB-based optimization evaluates stability, torque, and reachability to determine the best mounting position.

Key Components:

1.Parameters:

1. Platform: Dimensions, wheelbase, chassis height.
2. Arm: Mass, link lengths, end-effector.
3. Environment: Gravity.

2.Optimization:

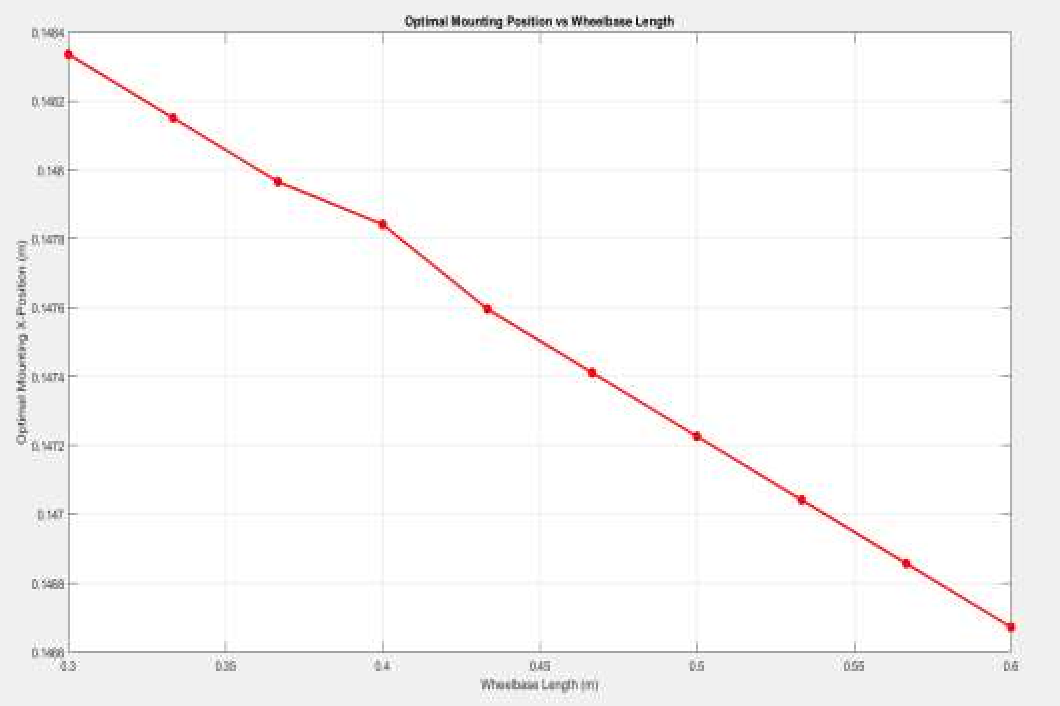
1. **Objective**: Minimize torque, penalize rear/edge positions, and maximize reach.
2. **Constraints**: Ensure stability and workspace within platform boundaries.

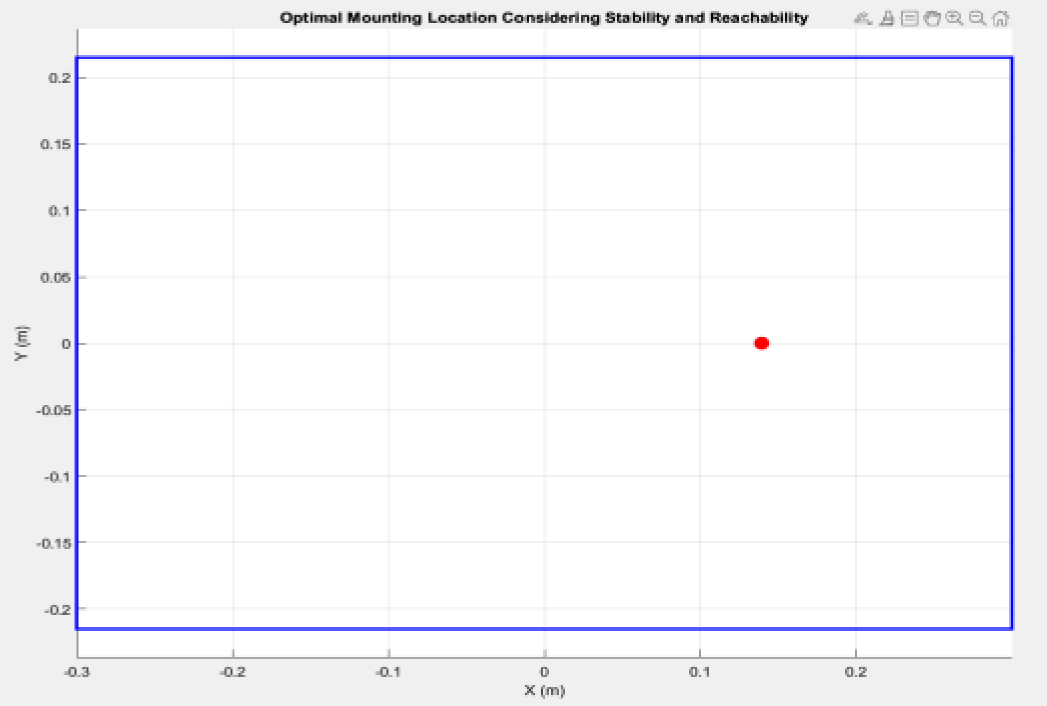
STABILITY ANALYSIS & OPTIMAL MOUNTING LOCATION

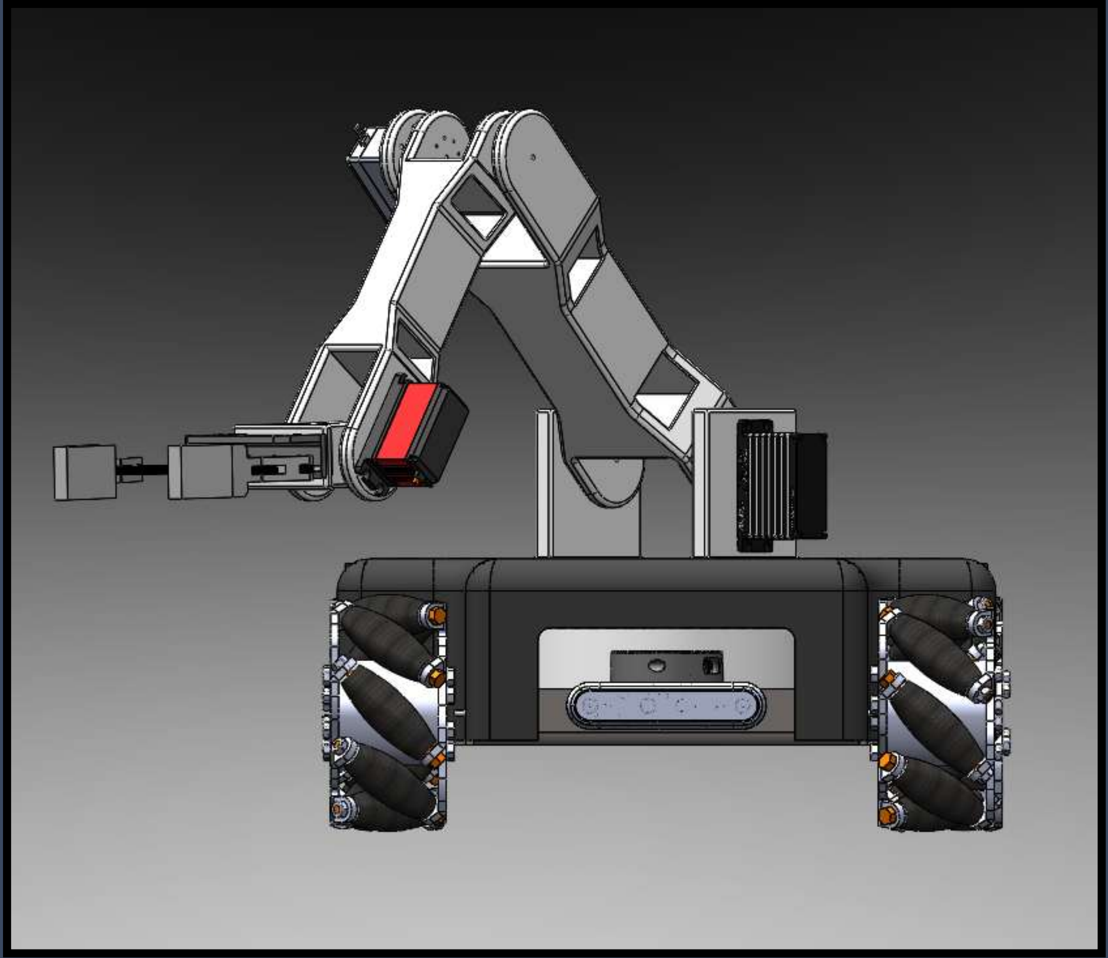
Findings:

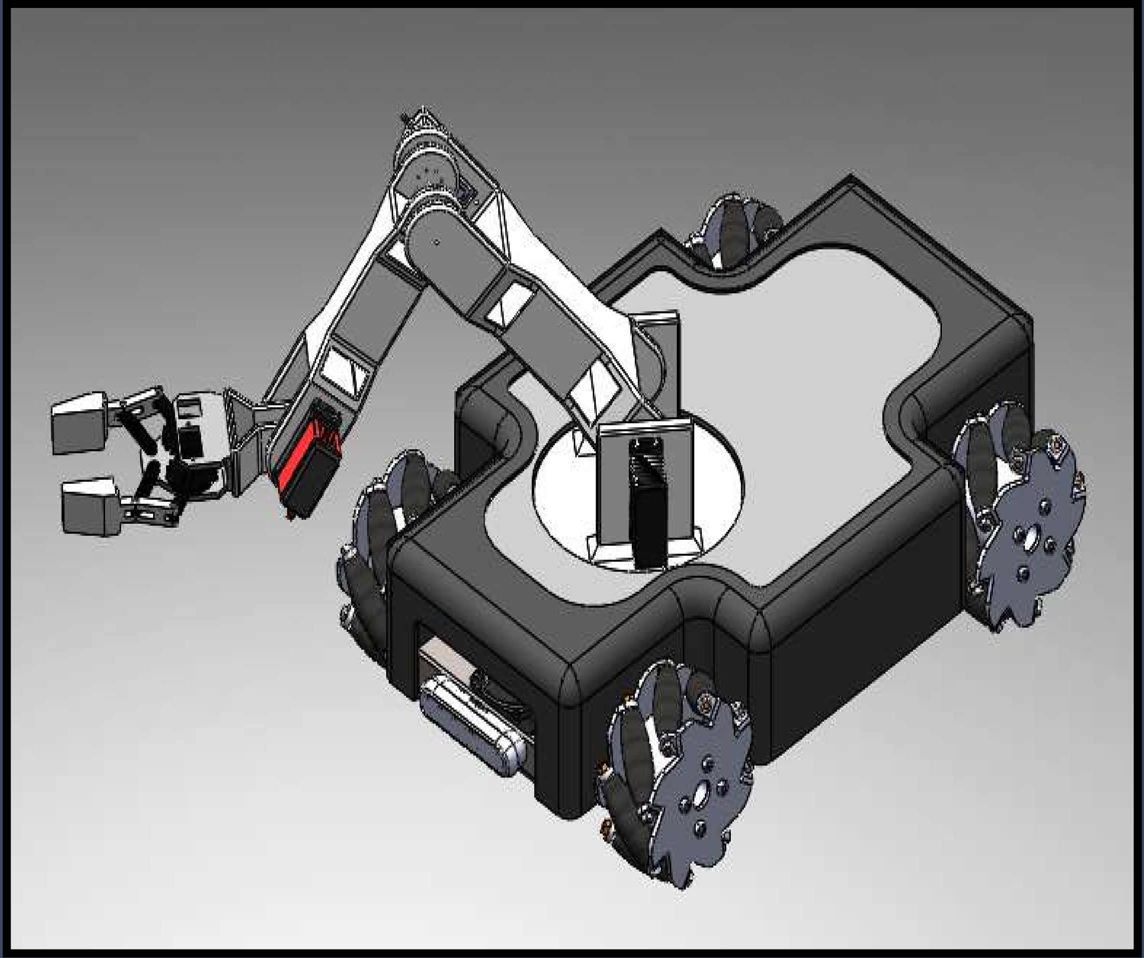
•**Optimal Mounting**:

- On a 60×43 cm chassis with a 45 cm wheelbase, the arm should be mounted in the front half for balance and reach.
- Placement minimizes tipping risk while maintaining stability and operational efficiency.









MOBILE MANIPULATOR DESIGN

POWER MANAGEMENT

- ❑ Servos (total): 5A (average per servo) × 3 = 15A
- ❑ High-torque servo: 10A
- ❑ DC Motors (CHR-GM37-3429E × 4): 1.5A × 4 = 6A
- ❑ Microcontroller, cameras, and sensors: 2A
- ❑ Total current: 15A + 10A + 6A + 2A = 33A

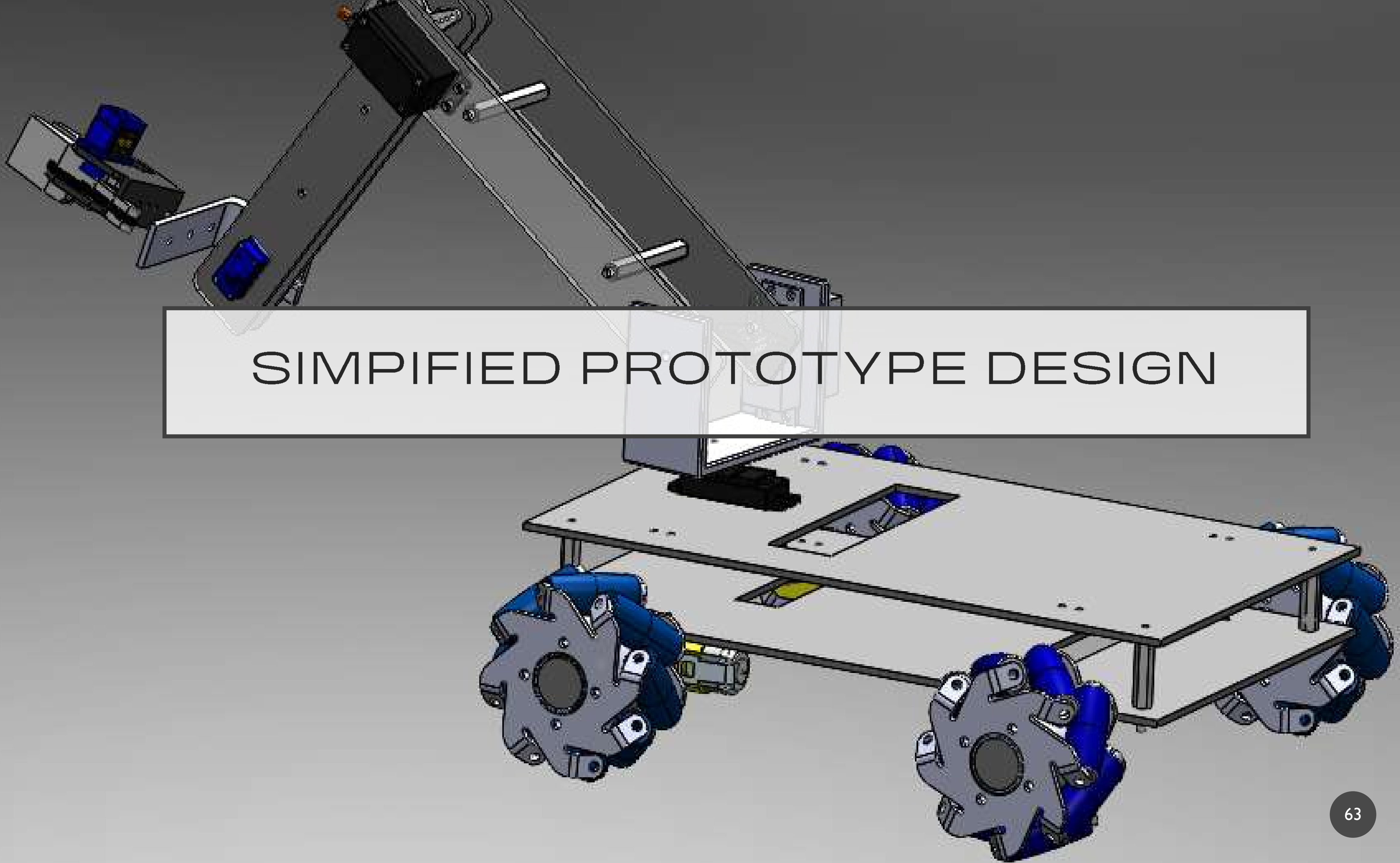
Assuming a 7.4V or 11.1V LiPo battery,

- ❑ For a 7.4V LiPo: 7.4V×33A = 244.2W

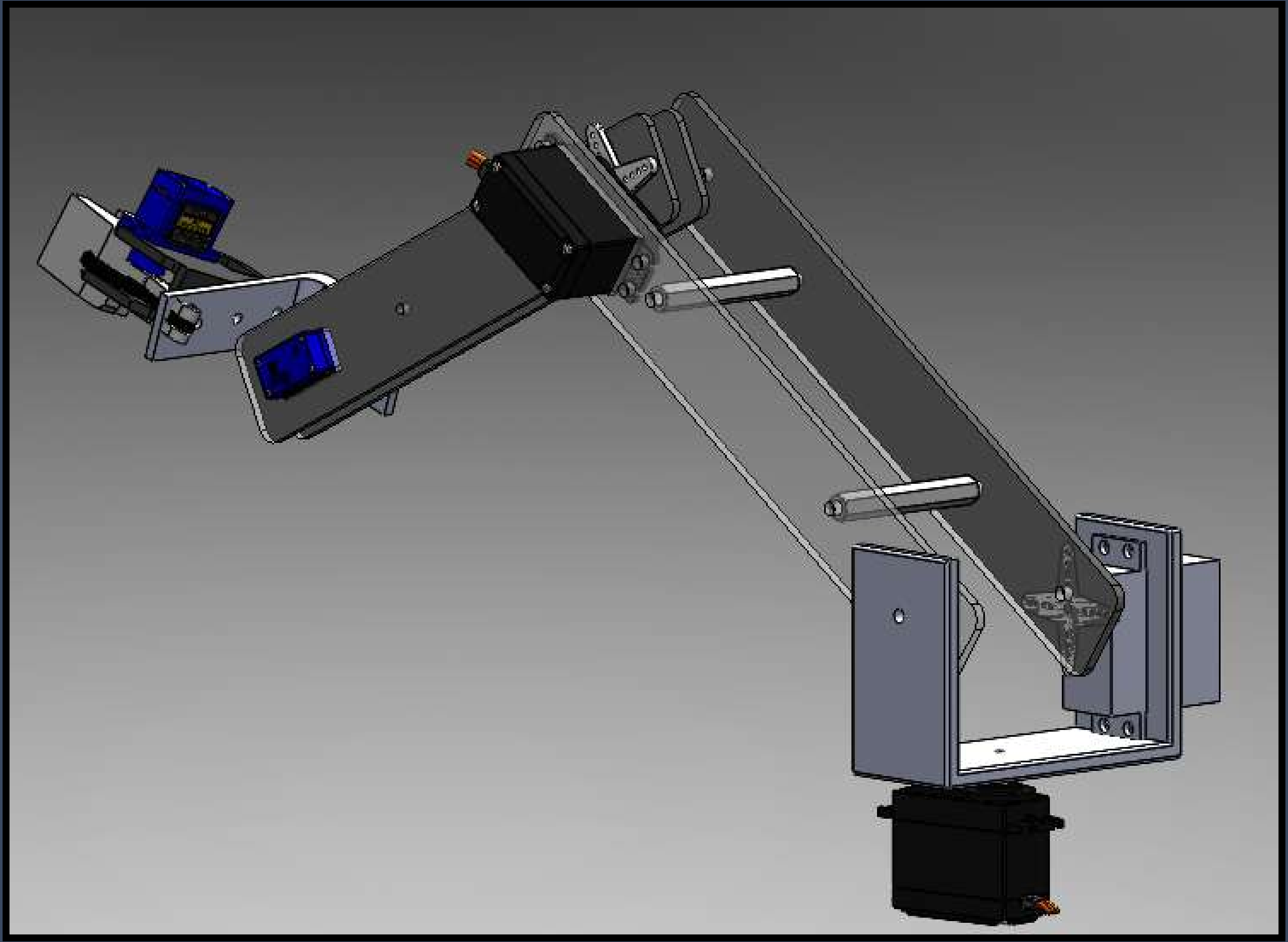
Continuous use of 1h,

- ❑ 7.4V LiPo: 244.2W/7.4V ≈ 33Ah

SIMPIFIED PROTOTYPE DESIGN



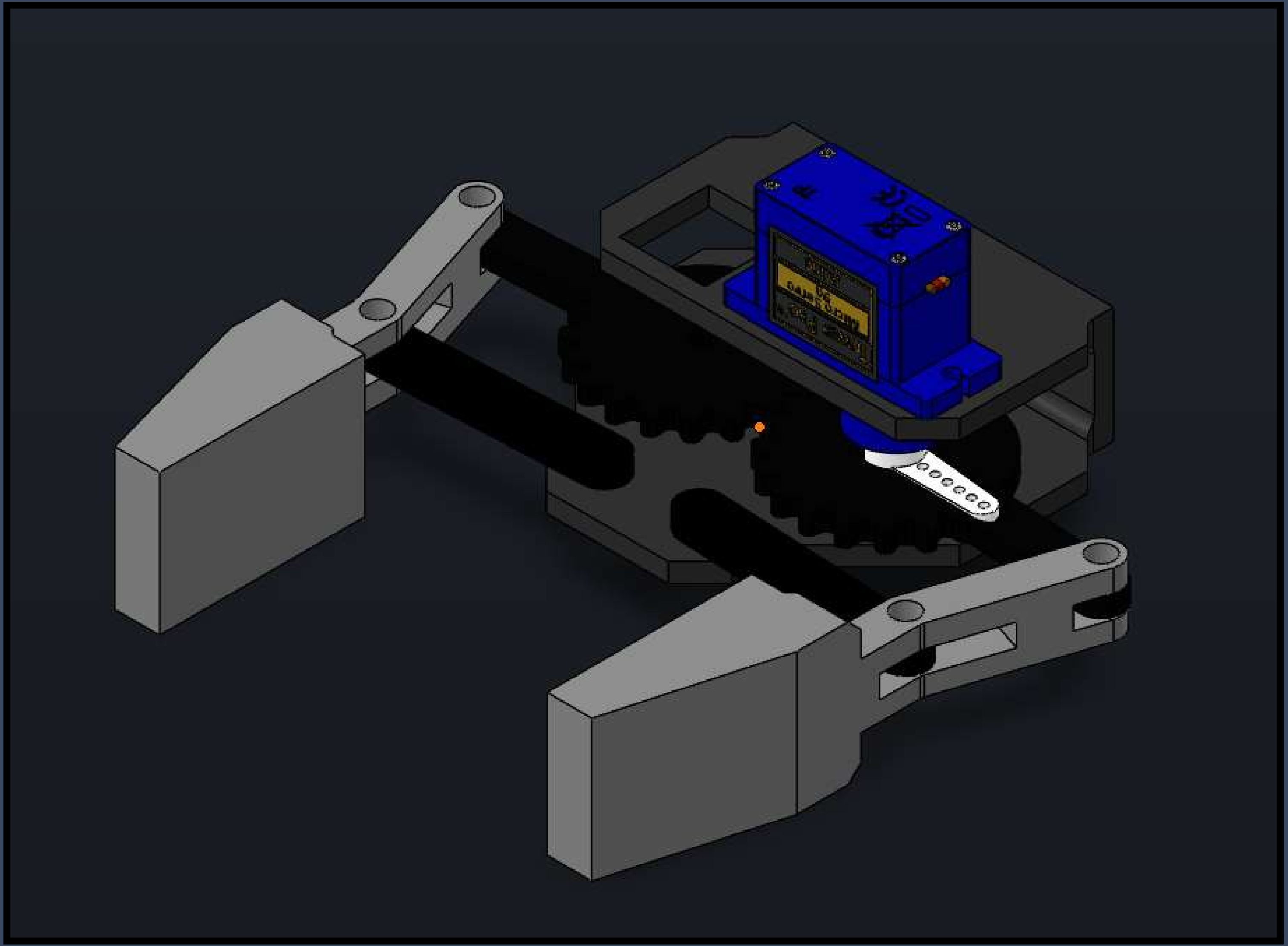
PROTOTYPE DESIGN – ROBOT ARM



Reduced Link Lengths by 25%

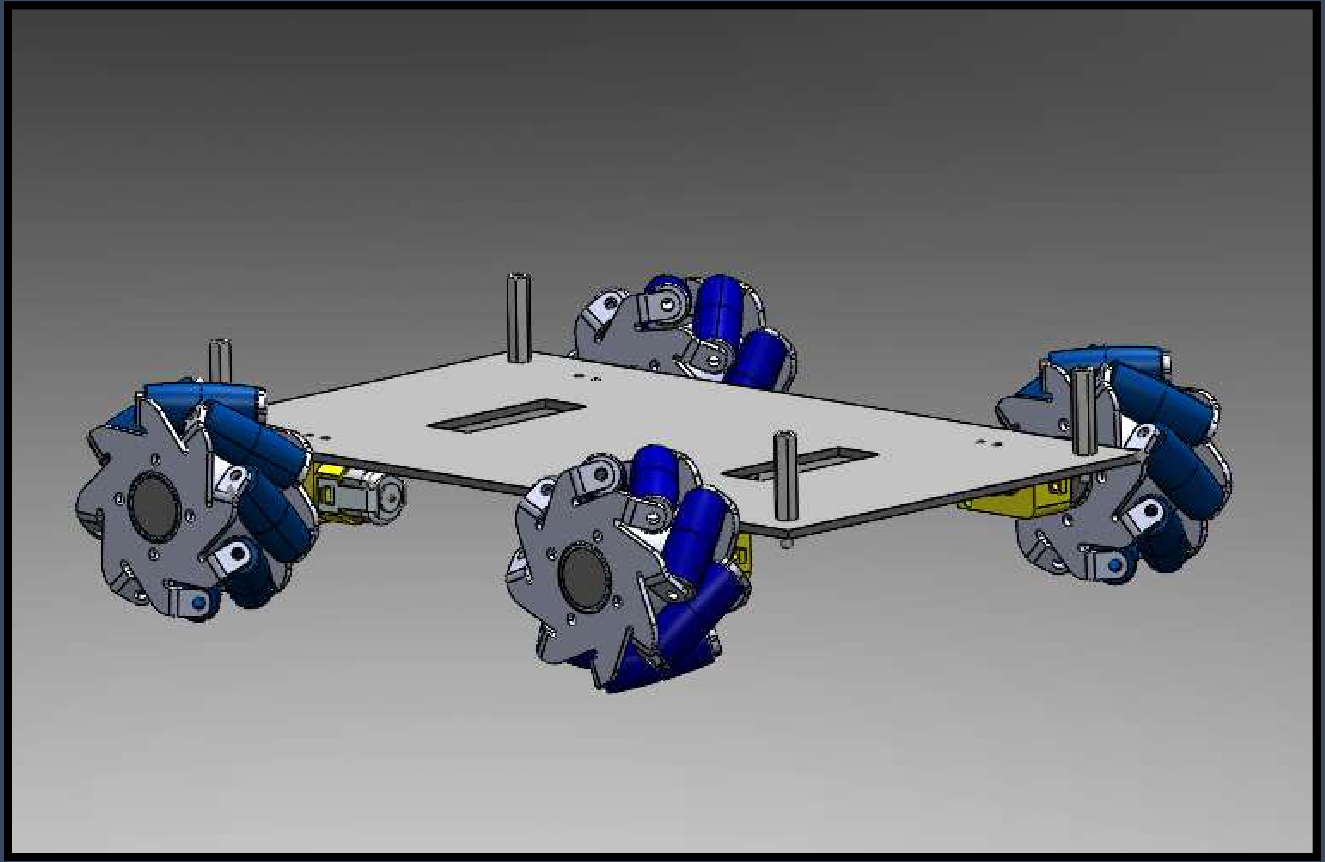
- Link 1 – 15cm
- Link 2 – 18cm
- Link 3 – 15cm

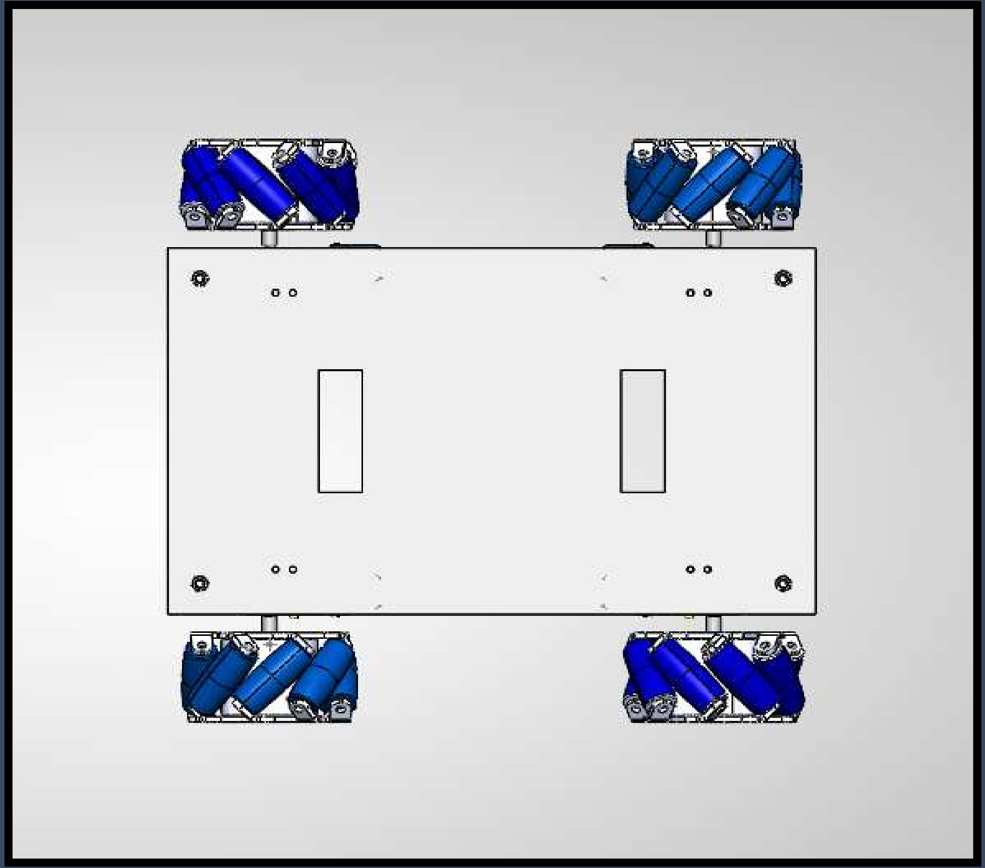
PROTOTYPE DESIGN – GRIPPER



- ❑ Reduced the size by 25%
- ❑ Reduced the payload to 100g

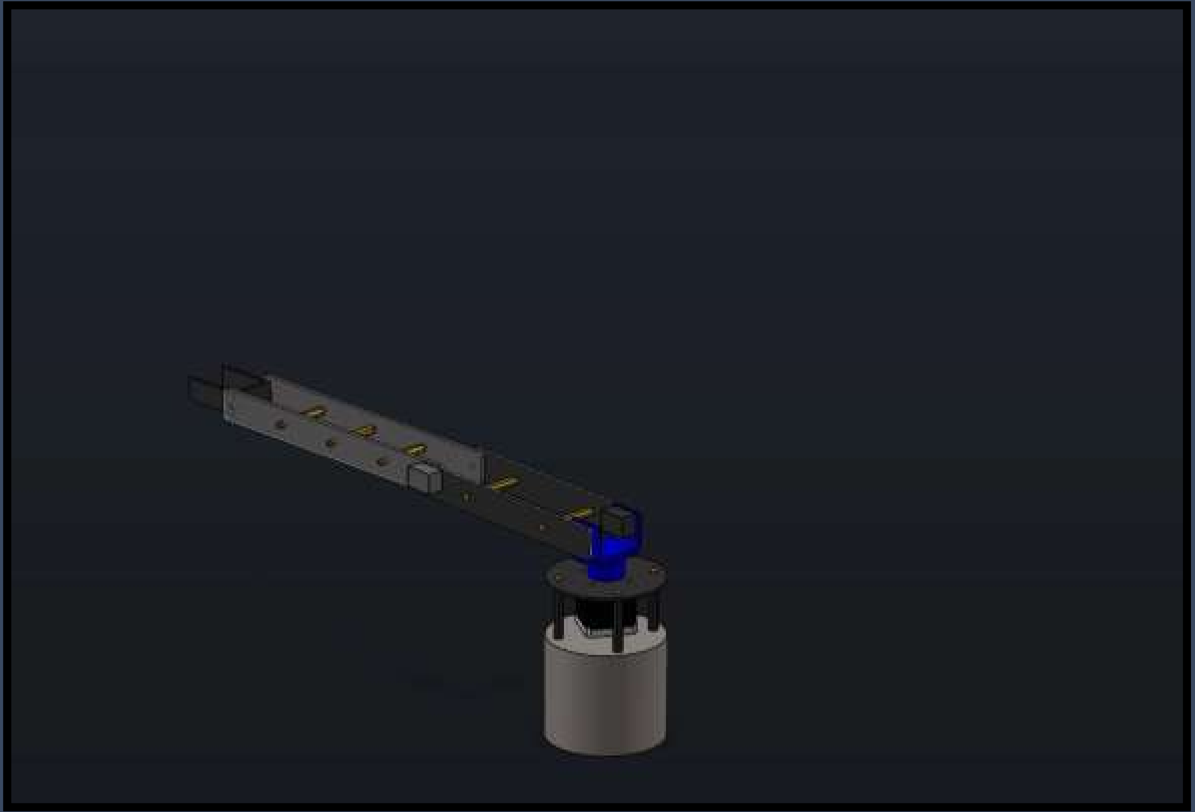
PROTOTYPE DESIGN – CHASSIS

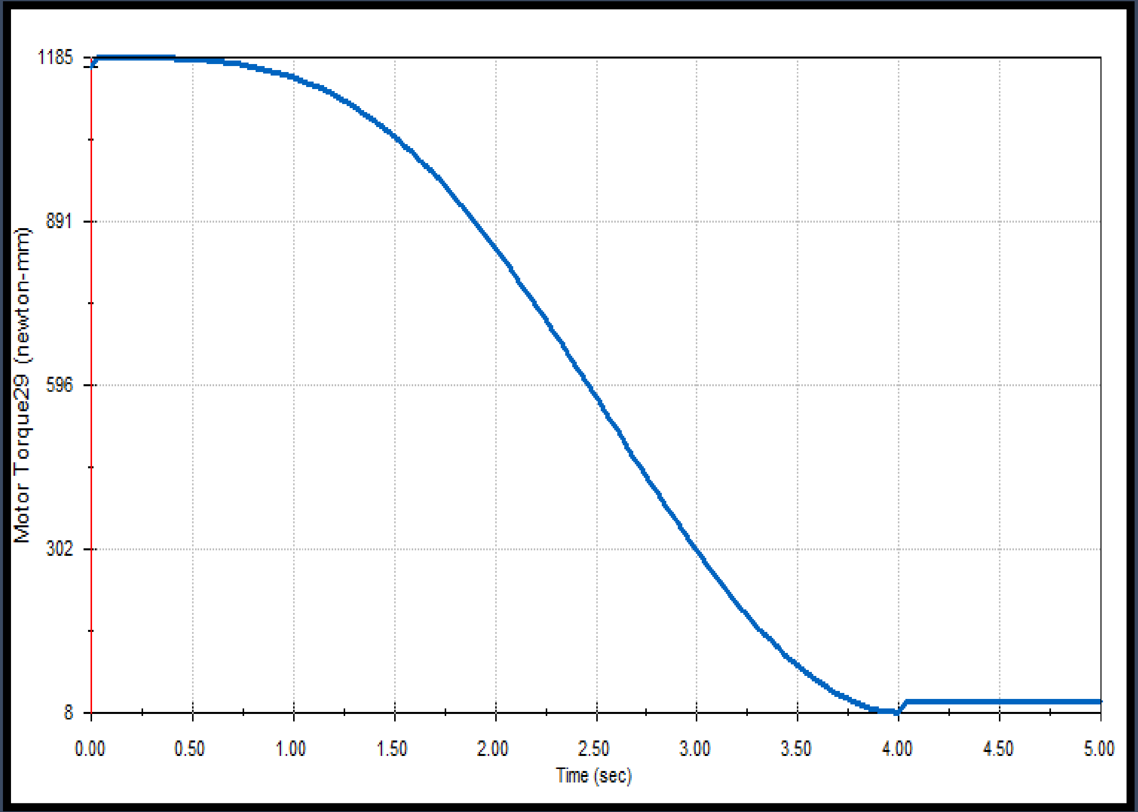




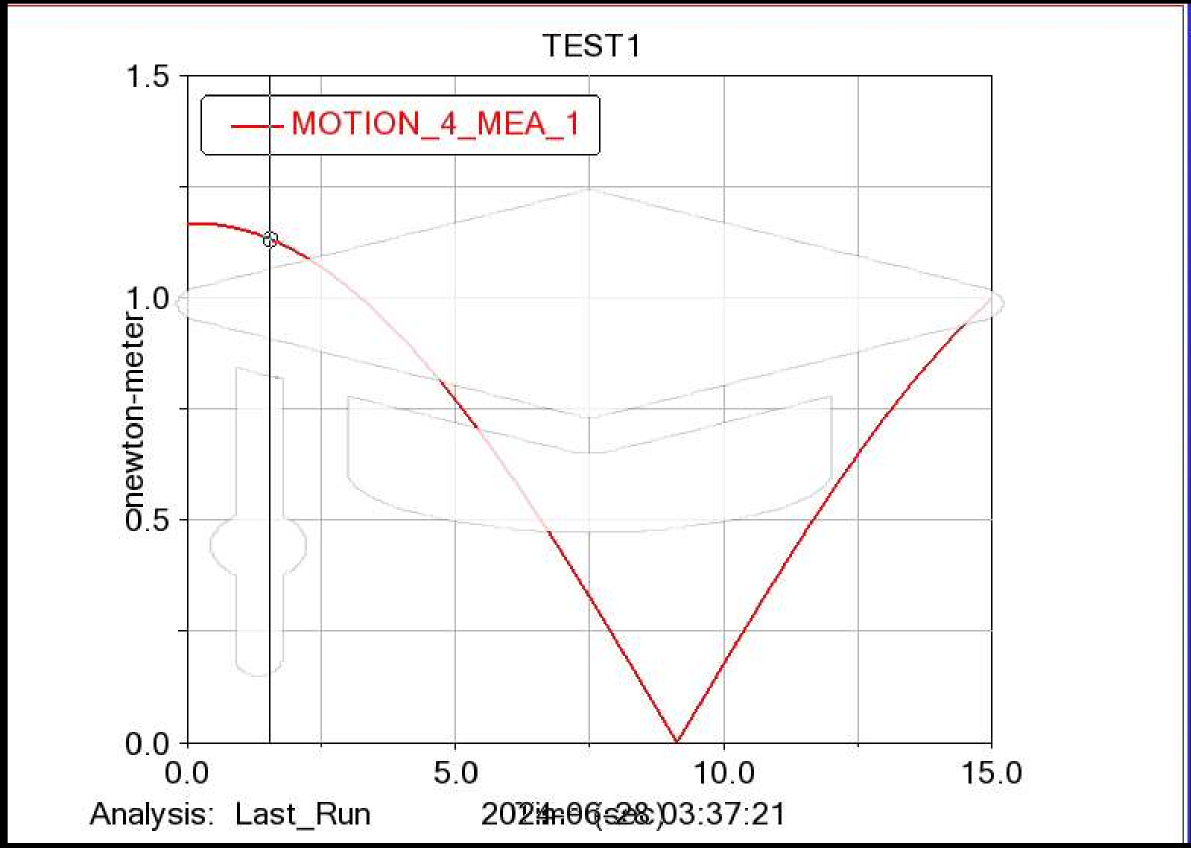
- ❑ Chassis Dimensions – 300 × 180 mm
- ❑ Wheel Size – 80mm

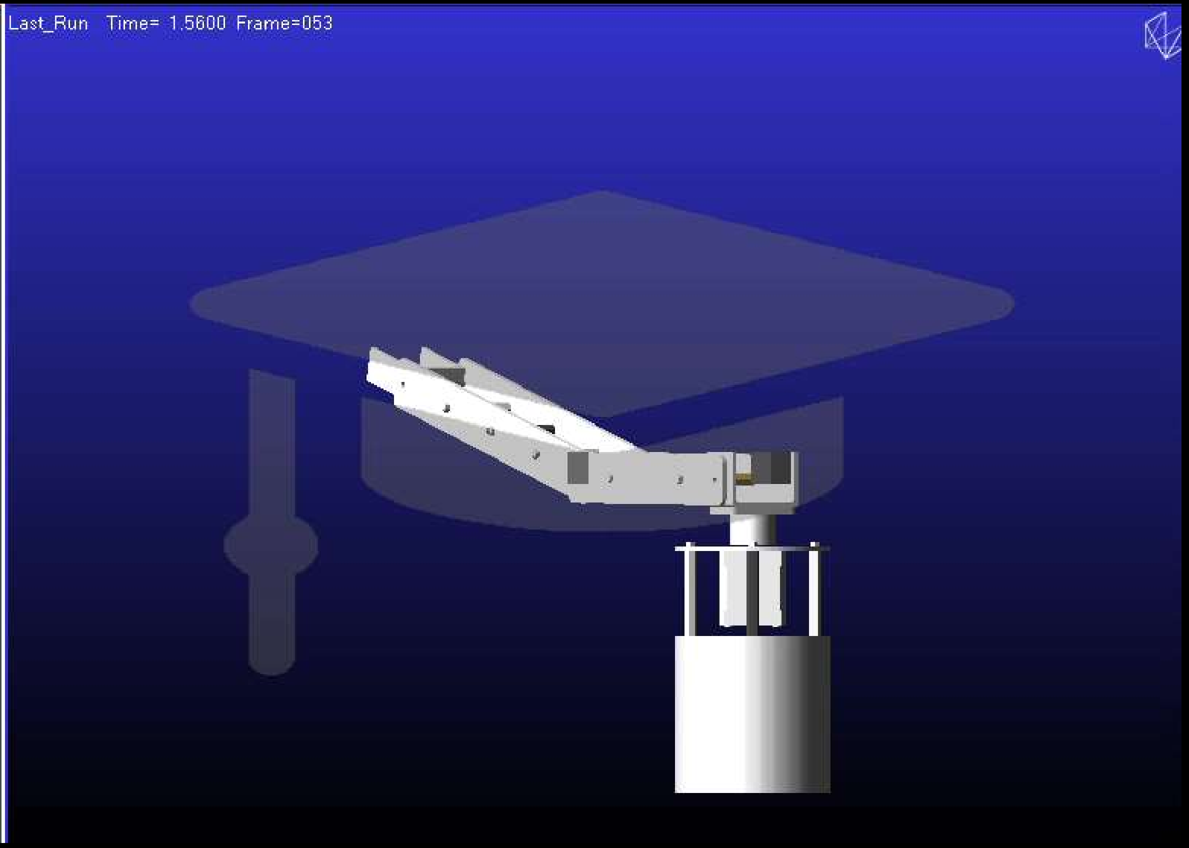
MOTOR TORQUE ESTIMATION FOR SHOULDER JOINT – SOLIDWORKS





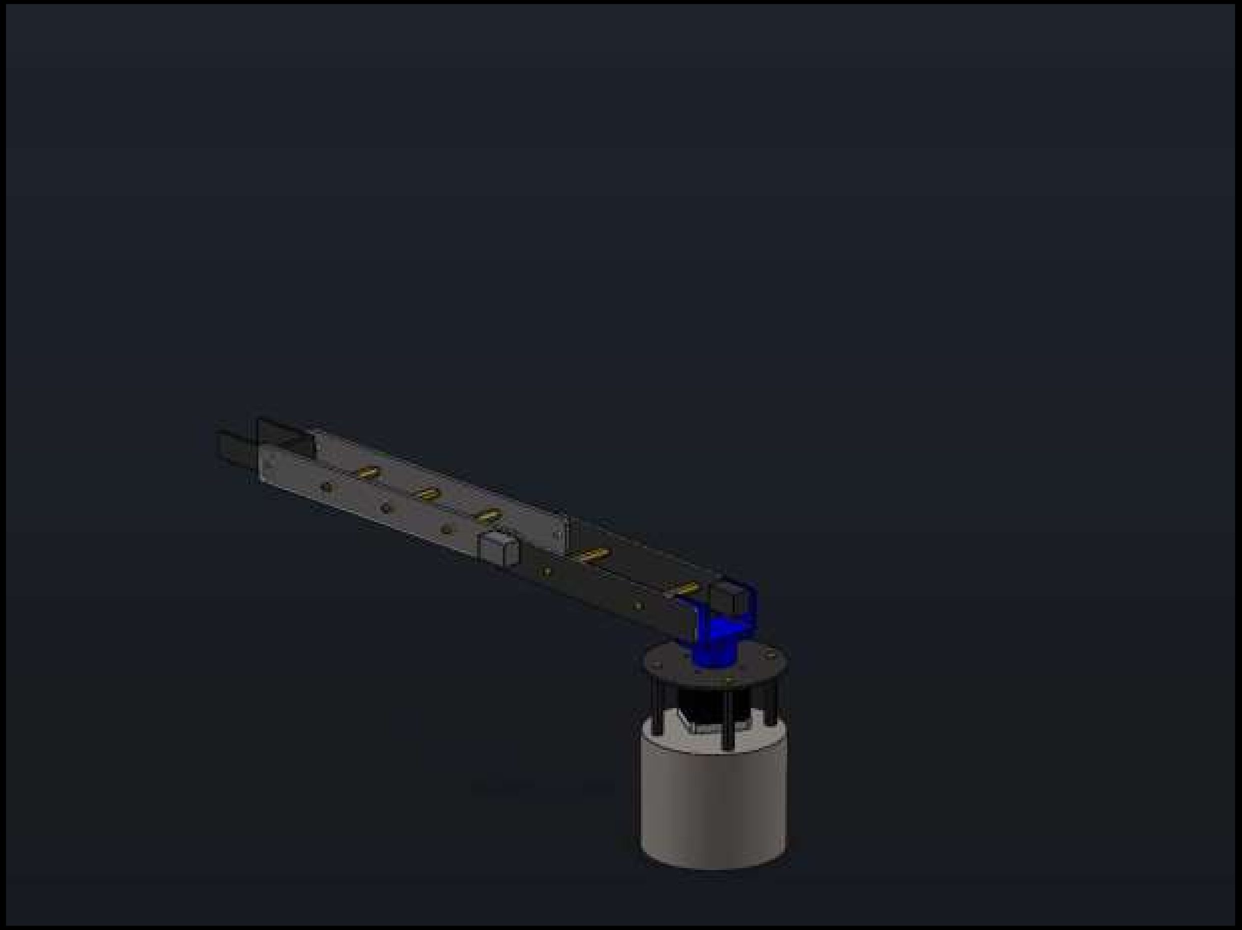
MOTOR TORQUE ESTIMATION FOR SHOULDER JOINT – ADAMS

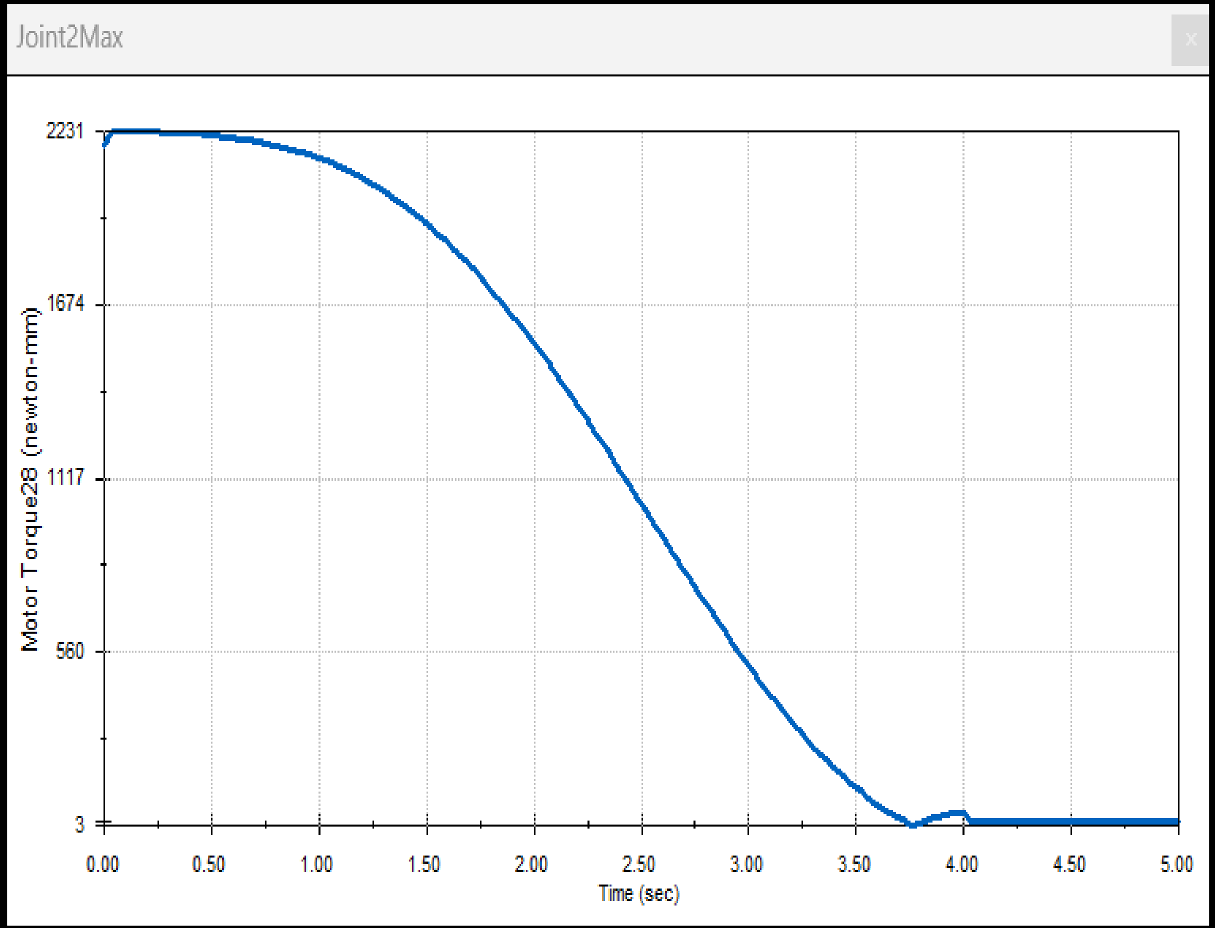




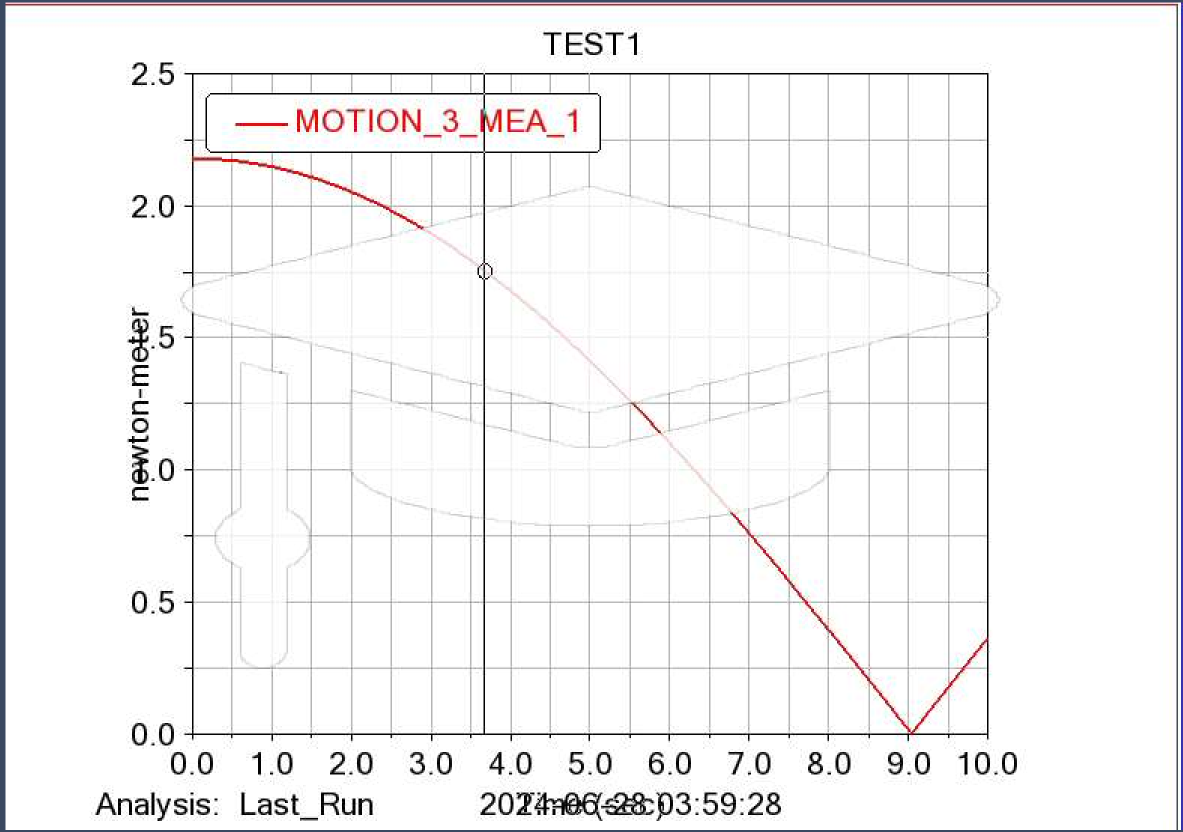
- Torque Required: 12kgcm
- Selected Motor: MG996R (20kgcm)
- Obtained Safety Factor: 1.6

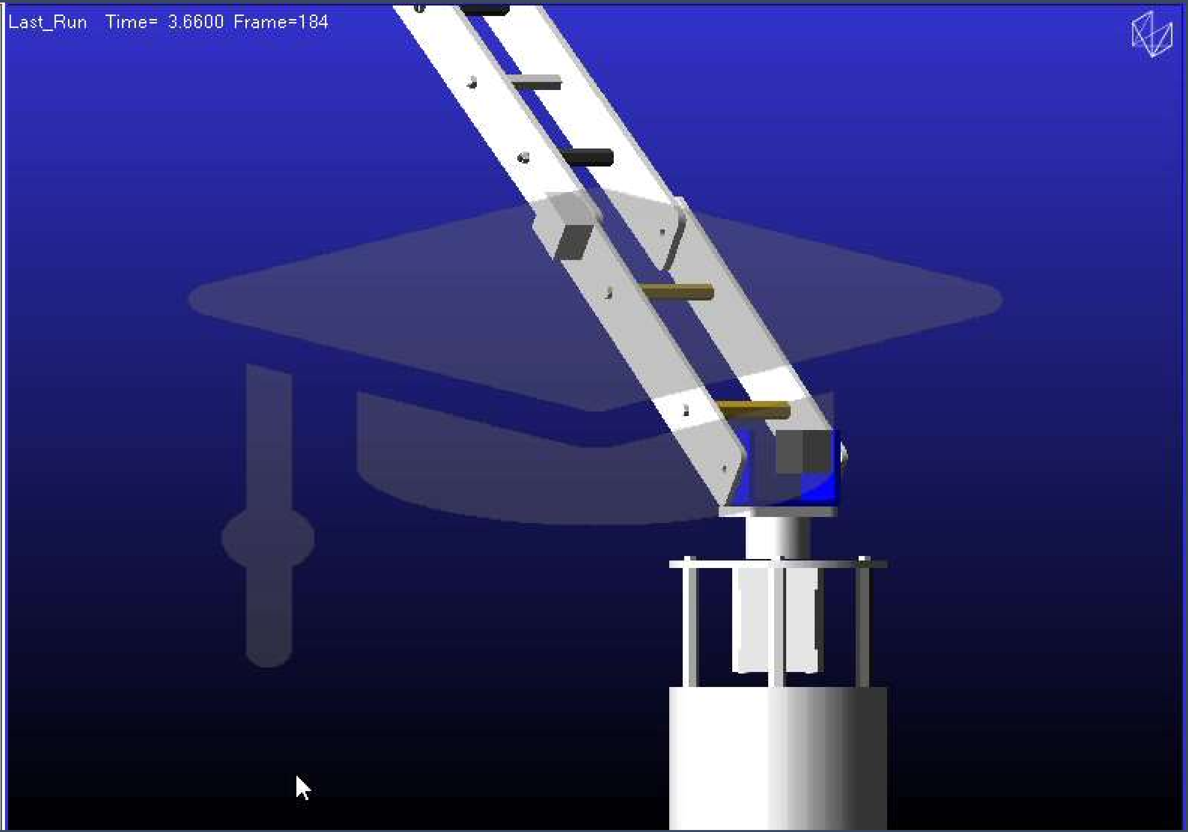
MOTOR TORQUE ESTIMATION FOR ELBOW JOINT – SOLIDWORKS





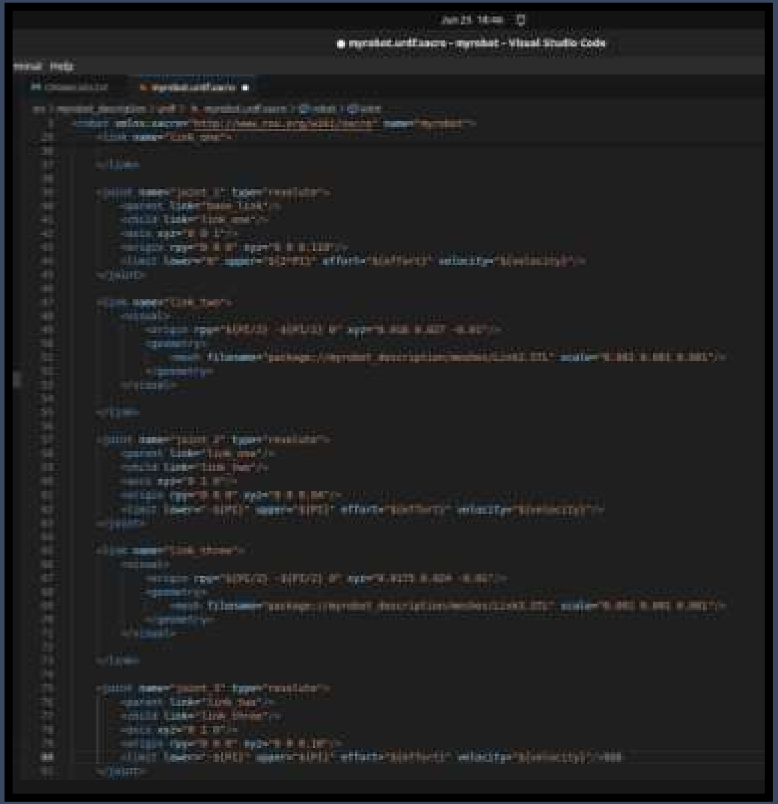
MOTOR TORQUE ESTIMATION FOR ELBOW JOINT – ADAMS

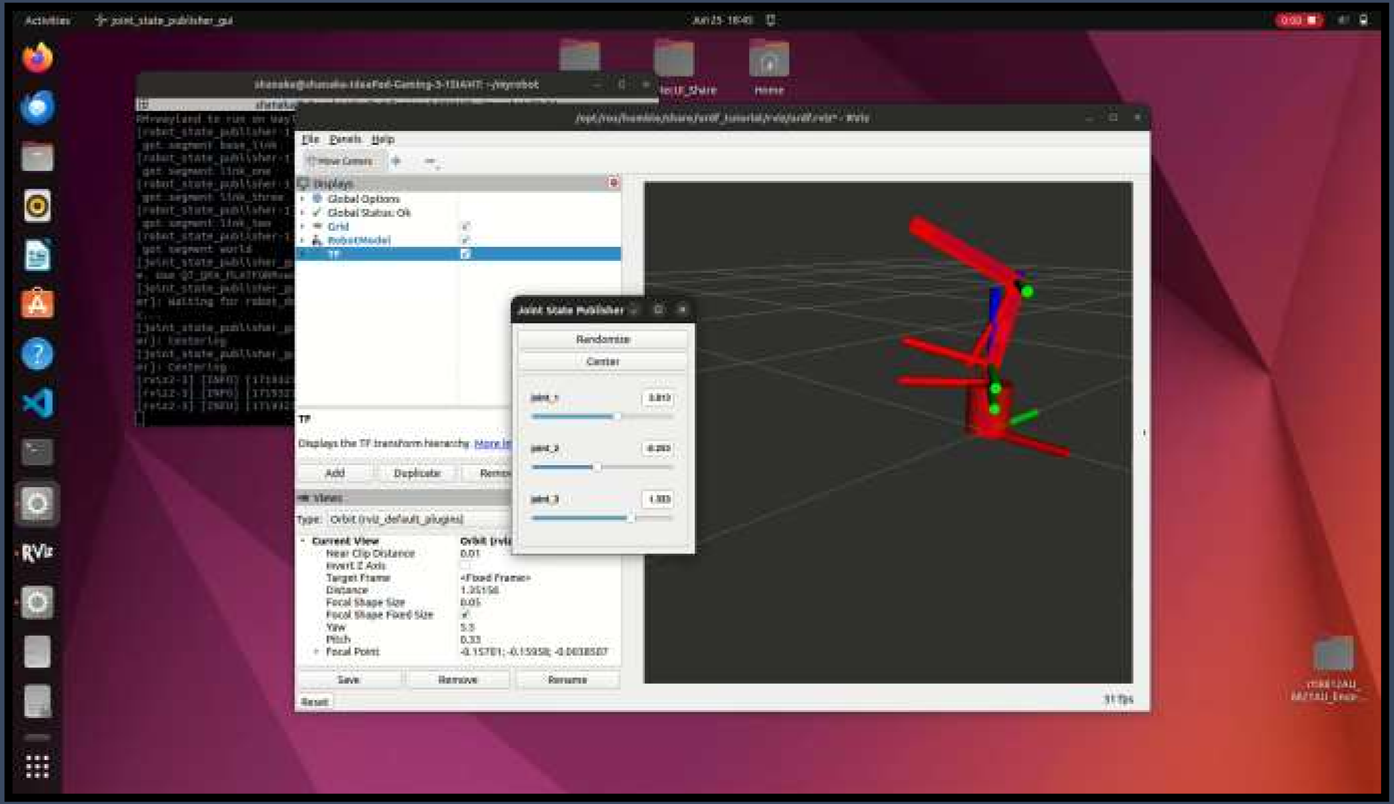




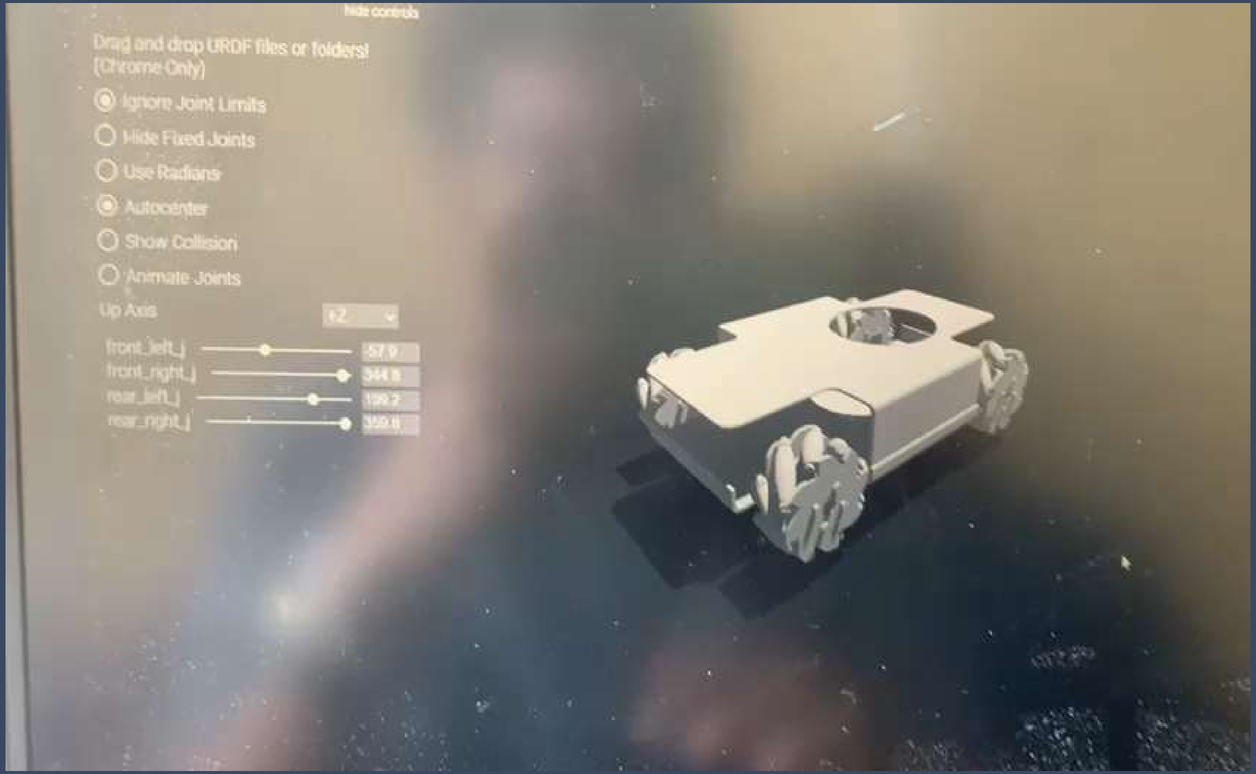
- Torque Required: 22.7kgcm
- Selected Motor: Futaba 30kgcm Digital Servo
- Obtained Safety Factor: 1.3

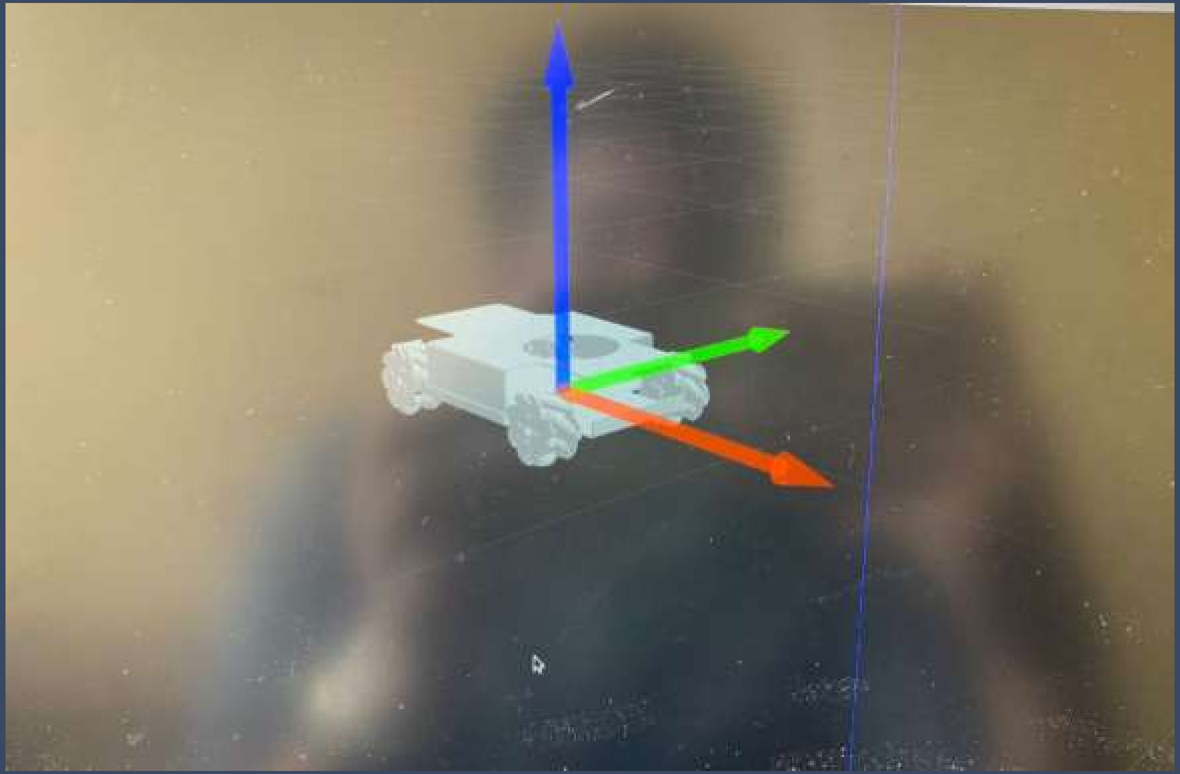
SIMULATIONS USING ROS2 – ARM





SIMULATIONS USING ROS2 – CHASSIS



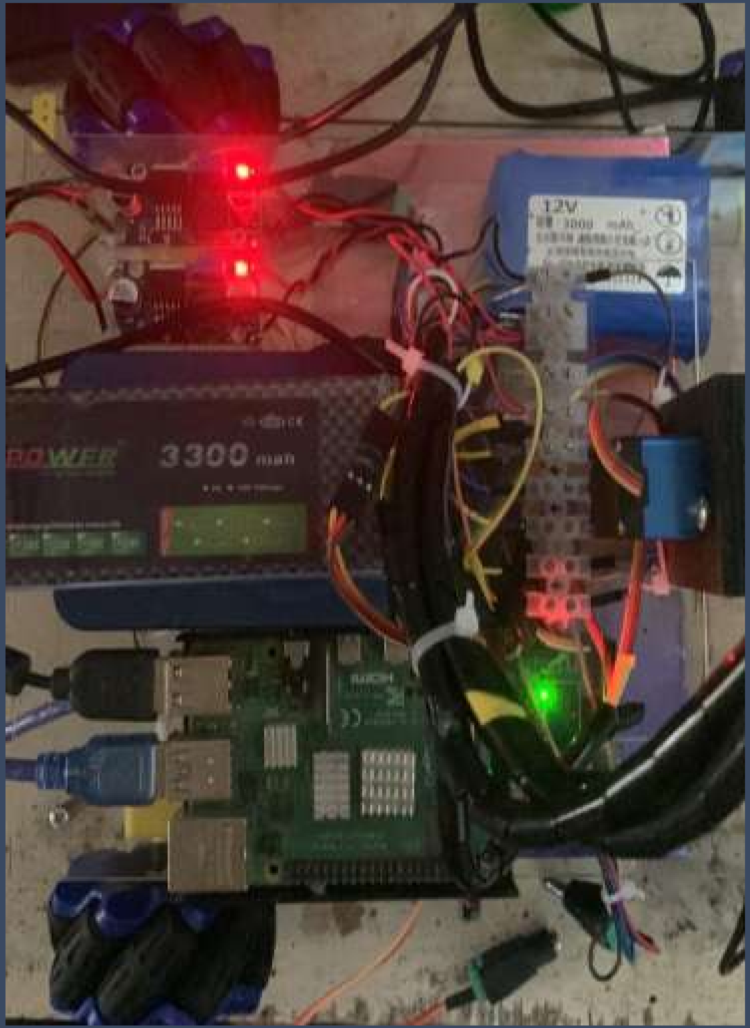


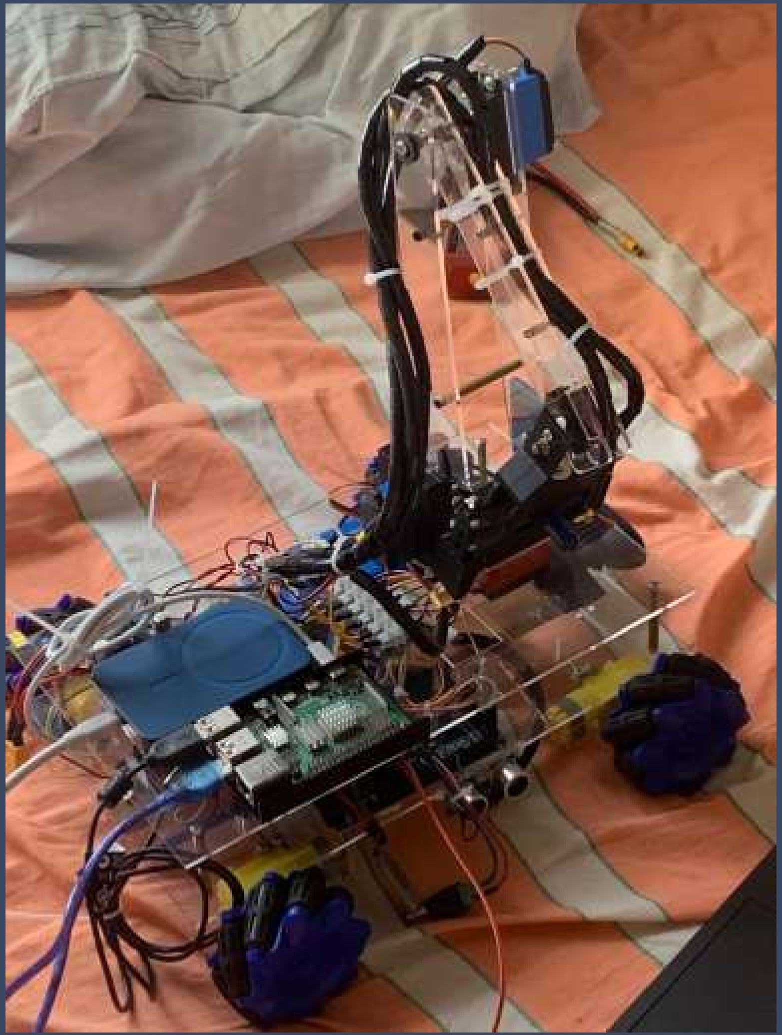
I Successfully launch the robot chassis on the gazebo environment. But I was unable to perform further simulations due to time problems.

PROTOTYPE DESIGN – GRIPPER

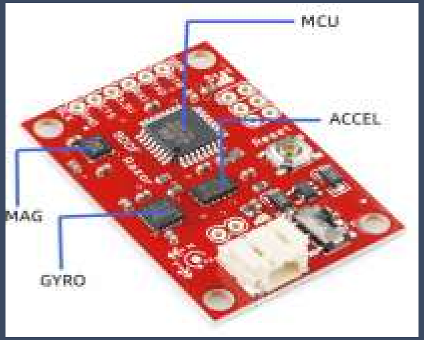
PROTOTYPE DESIGN – GRIPPER

FINAL LOOK





CONTROL SYSTEM



ULTRASONIC SENSORS

ENCORDERS

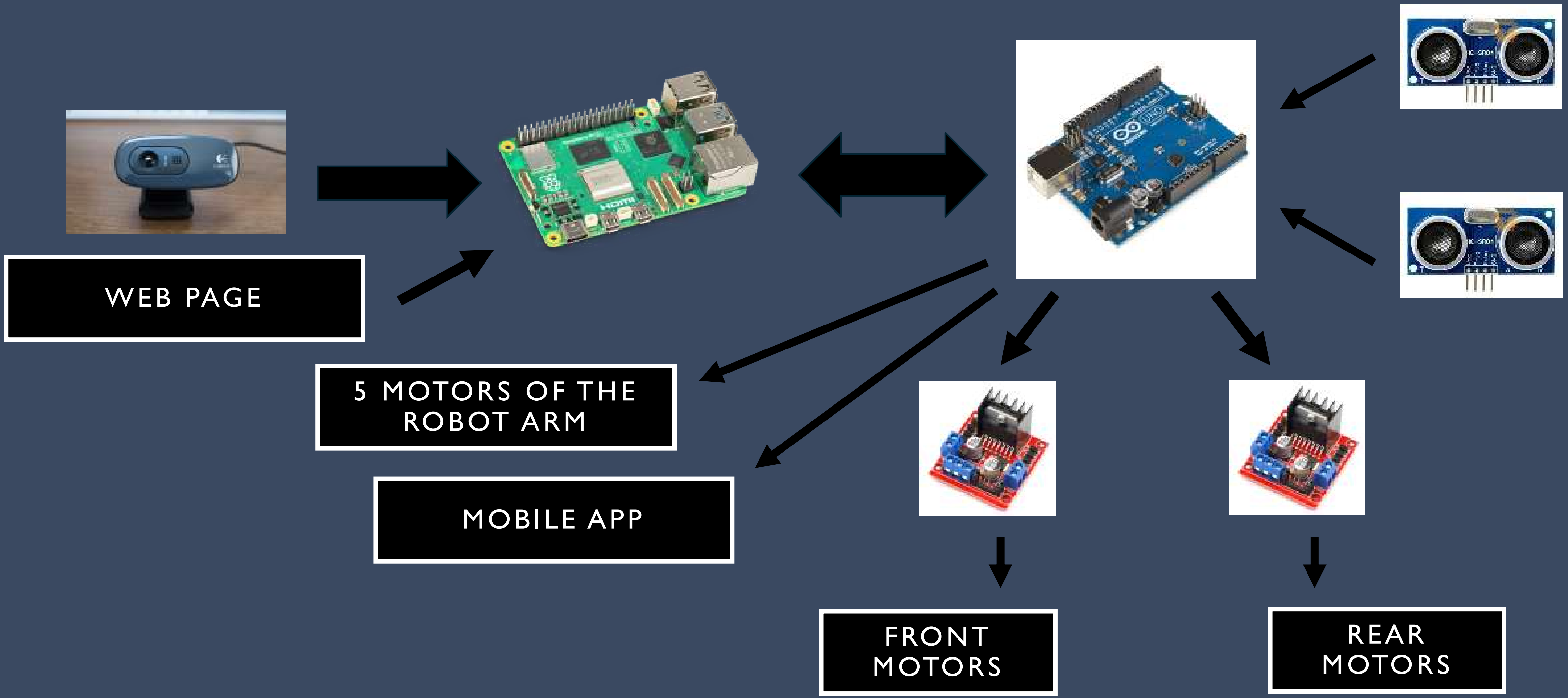
MOTOR CONTROLLERS

MOTORS

CONTROL SYSTEM – DATA FLOW

- **Perception**:
  - Depth Camera + LiDAR + IMU: Feed processed data to High-level controller.
  - Use sensor fusion to increase the accuracy.
- **Navigation**:
  - Use SLAM algorithms to map the environment and determine the robot's position.
  - Combine wheel odometry (from encoders) and IMU data for accurate localization.
- **Actuation**:
  - High level controller sends high-level commands (e.g., direction, speed) to the Arduino.
  - Low level controller executes commands via motor controllers.

PROTOTYPE CONTROL SYSTEM



CONTROL SYSTEM – NAVIGATING

- Object Detection:
  - Uses a camera and HSV color filtering to detect blue objects in real-time for a fixed sized object.

- Position Estimation:
  - Calculates object depth (Z) and lateral offset (X) using camera calibration.
  - Since the real-world height of the object is constant, the apparent height in the image (h) directly correlates with the distance.
  - As the object moves closer, it appears larger in the frame, and h increases, resulting in a smaller calculated Z.
  - Smooths values with Exponential Moving Average (EMA) for stability.

- Motion Control:
  - Commands the robot to move forward, turn, or stop based on the object's position.
  - Implements proportional control for precise movement and alignment.

- Actuation:
  - Sends movement commands to the robot via Arduino for execution.

CONTROL SYSTEM – NAVIGATING

CONTROL SYSTEM – ROBOTIC ARM

- Camera Setup:
  - Captures live video to detect objects, with resolution optimized for performance.
- Object Detection:
  - Identifies blue objects using HSV color filtering.
  - Validates objects based on size and shape.
- Depth and Position Estimation:
  - Calculates the object’s 3D position (X, Y, Z) using the object's size, camera calibration, and known object height.
  - Applies offsets for camera position relative to the robot base.
- Buffering and Stabilization:
  - Collects object positions in a buffer for 2 seconds to stabilize the detection.
- Inverse Kinematics:
  - Computes joint angles to reach the averaged position.
- Sends calculated angles to Arduino for robotic arm movement.
- Visualization:
  - Displays the robot arm's position using a 3D plot after executing the motion.

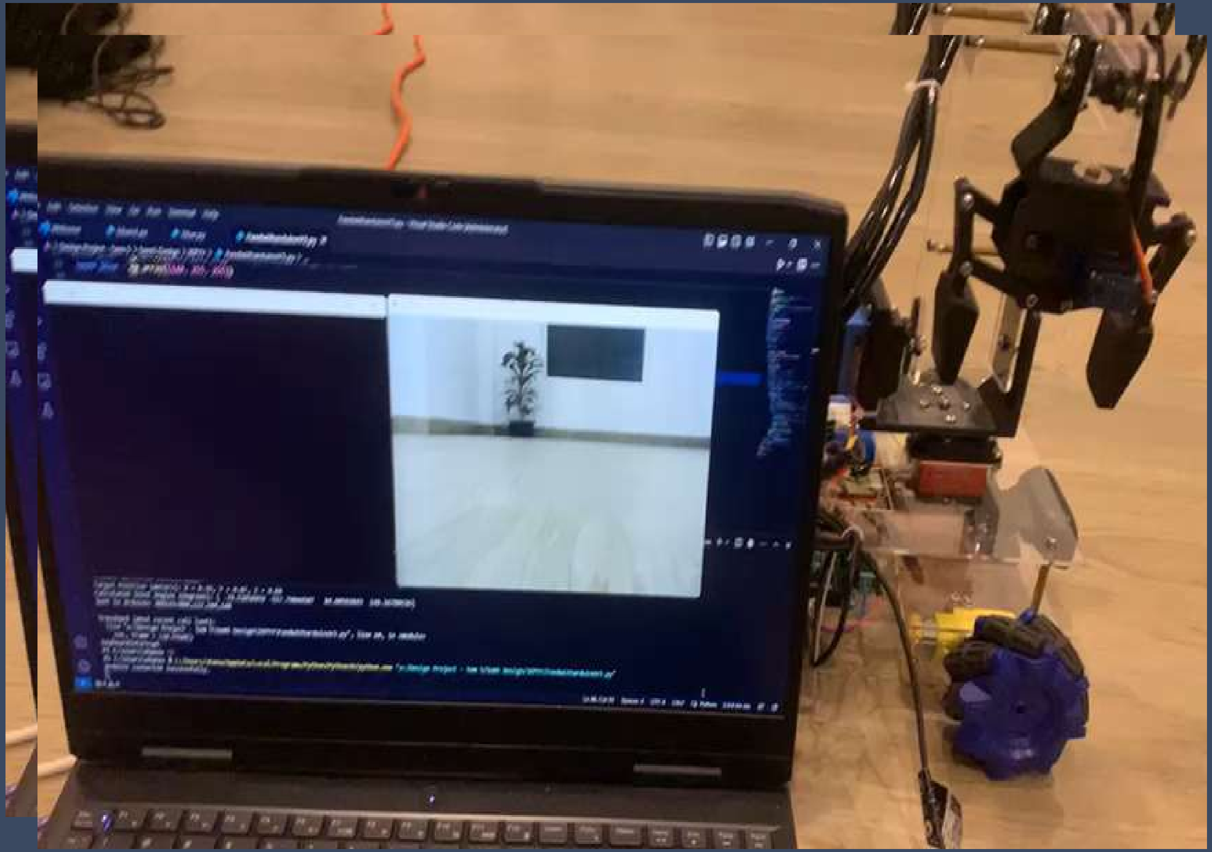
CONTROL SYSTEM – ROBOTIC ARM

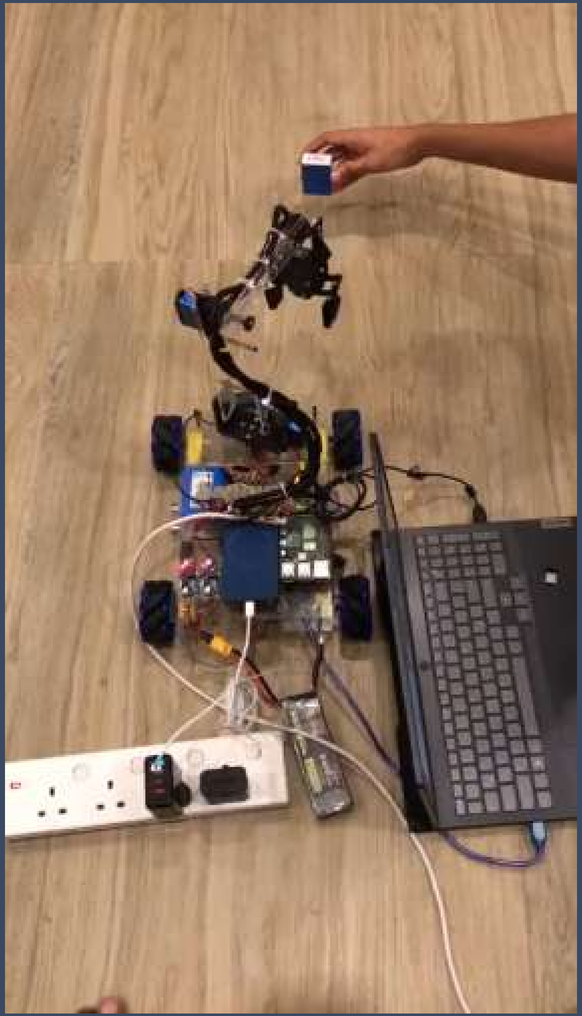
IKPy Usage in the Robotic Arm:

- Robot Model Loading: Reads the arm's structure from a URDF file to create a kinematic chain.
- Target Position Calculation: Converts detected object's coordinates (X,Y, Z) into joint angles using inverse kinematics.
- Joint Angle Computation: Ensures realistic movement by adhering to physical constraints and joint limits.
- Servo Control: Sends computed angles to the Arduino to move the servos and position the end effector accurately.
- Visualization: Plots the arm's 3D position for debugging and validation.

IKPy simplifies complex kinematics, ensuring precise and smooth arm movement to the target location.

CONTROL SYSTEM – ROBOTIC ARM

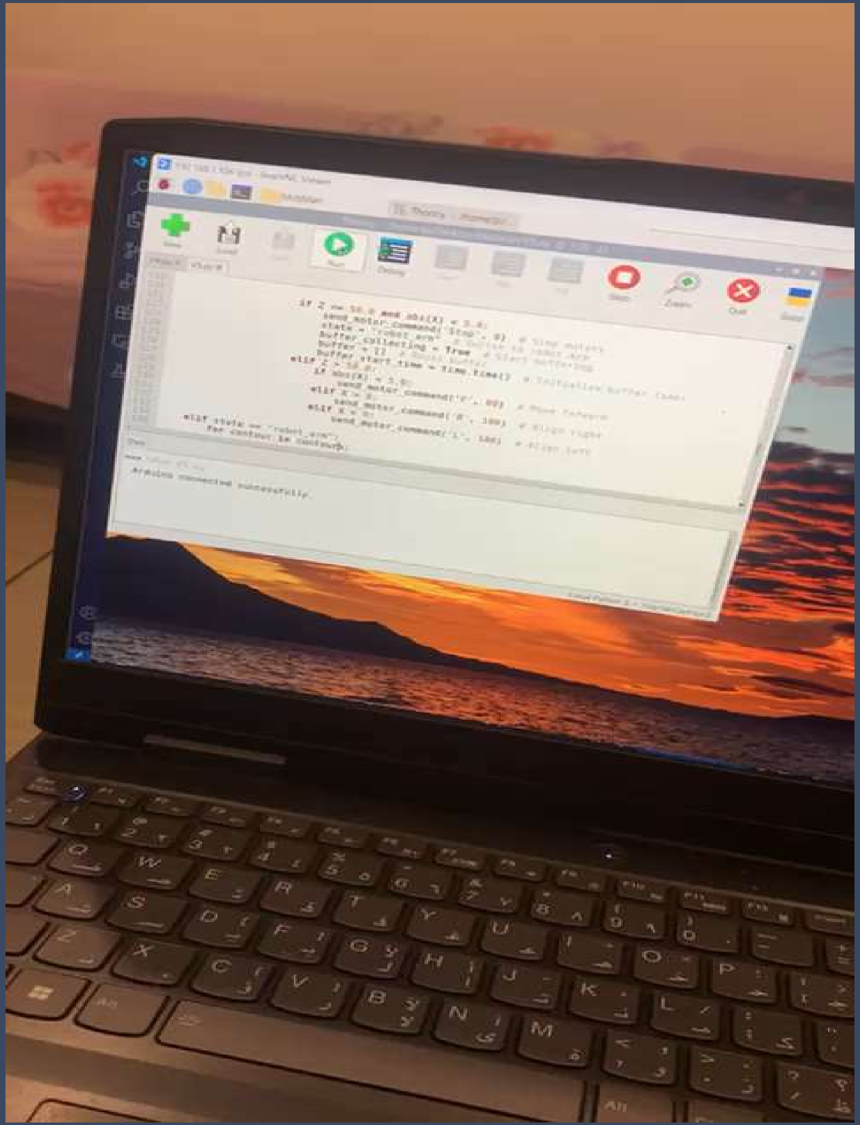


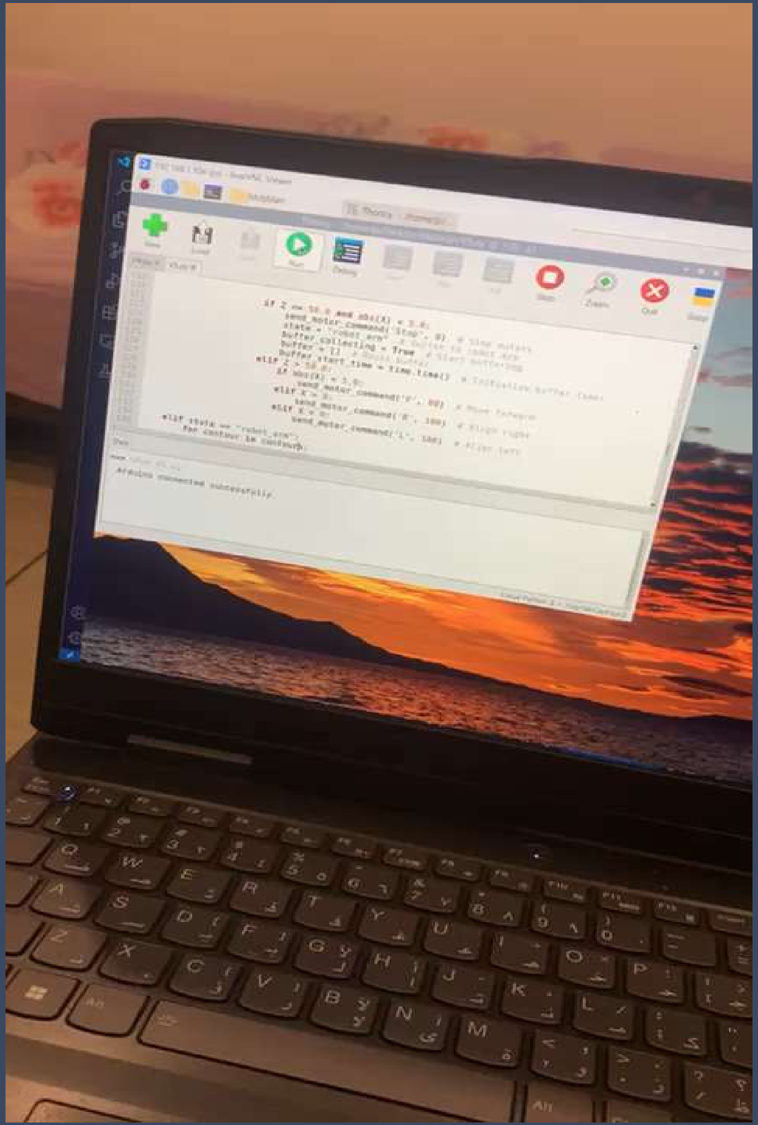


CONTROL SYSTEM – MOBILE MANIPULATOR

- Chassis Mode:
  - Object Tracking: Detects the object's position relative to the robot.
  - Navigation: Commands the base to move forward, align left, or right, based on object position.
  - Switches to manipulator mode if the object is within a predefined range and aligned laterally.
- Manipulator Mode:
  - Computes the object's 3D position (X, Y, Z) using camera parameters and object height.
  - Buffering: Stabilizes the target position by averaging multiple frames.
  - Inverse Kinematics: Uses IKPy to calculate joint angles for the manipulator to reach the target.
  - Execution: Sends calculated joint angles to Arduino for precise arm movement.
- State Transitions:
  - Returns to chassis mode after the manipulator completes its task, enabling seamless integration between navigation and manipulation.
- Visualization and Feedback:
  - Displays live video feed with bounding boxes, depth, and target coordinates for real-time monitoring.
  - Waits for Arduino's confirmation after completing each action.

CONTROL SYSTEM – MOBILE MANIPULATOR





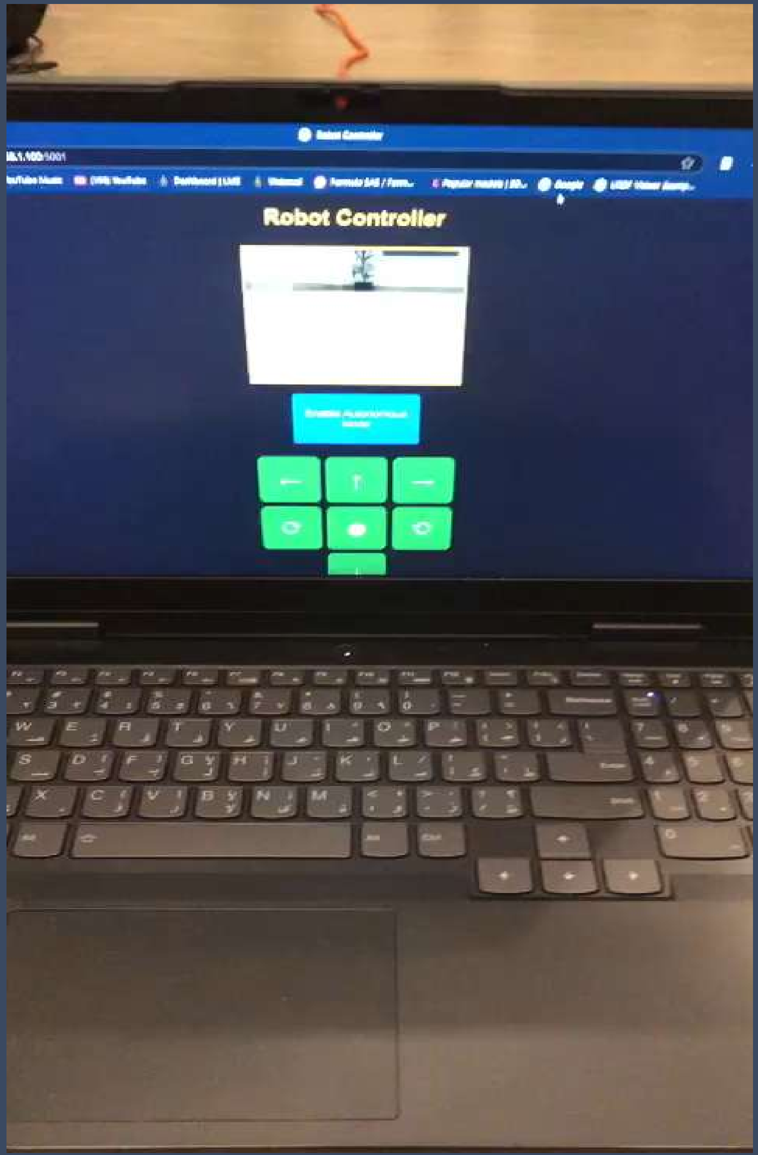
CONTROL SYSTEM – WEB PAGE

- Control Buttons for Manual Movement:
  - Buttons to control the base movement in different directions (forward, backward, left, right).
  - Stop button for halting all movement.
  - Dedicated buttons for Clockwise (CW) and Counter-Clockwise (CCW) rotations for fine angular adjustments.
  - Use Case: Enables the user to manually maneuver the robot base when precise or direct control is required.
- Sliders for Manipulator Control:
  - Individual sliders to adjust the angles of the manipulator's joints (e.g., base, shoulder, elbow, wrist).
  - A slider for controlling the gripper position.
  - Real-time display of the current slider values.
  - Use Case: Provides intuitive control of the robot arm's joints, allowing users to manipulate the arm into desired positions.

CONTROL SYSTEM – WEB PAGE

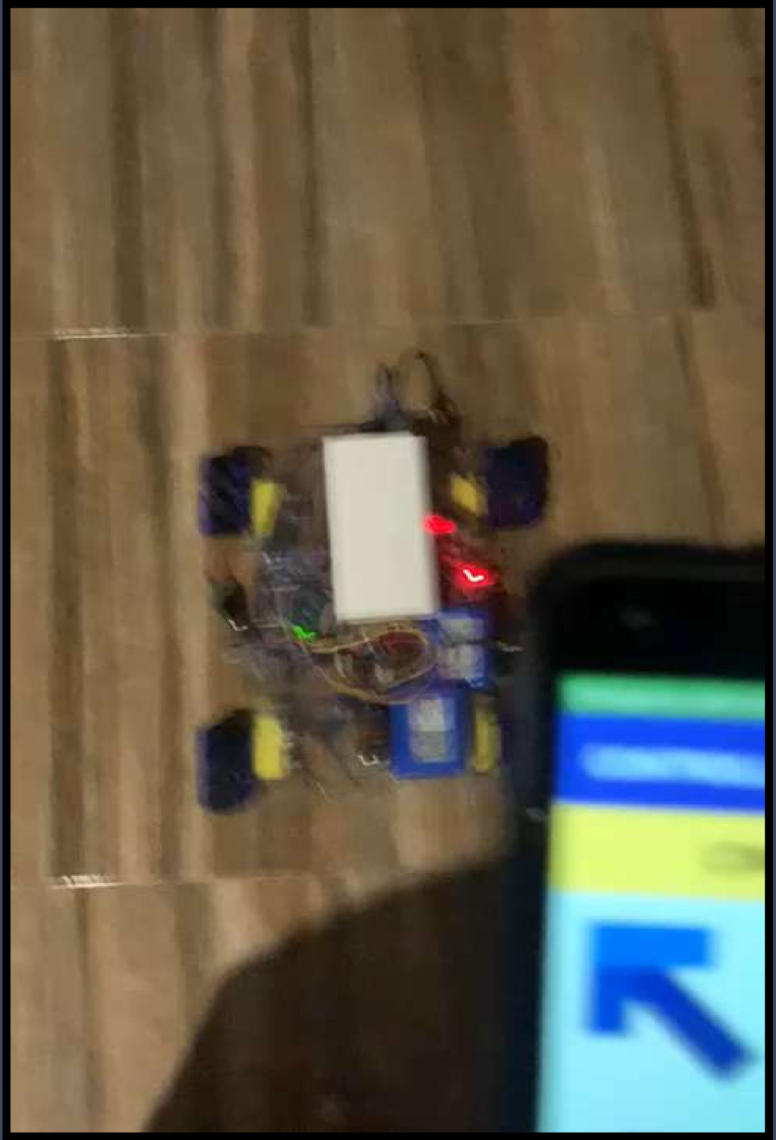
- Streams live video from the robot's camera.
  - Visualizes the robot's field of view in real-time.
  - Use Case: Helps the operator monitor the environment and adjust actions based on visual feedback.
- Forward Kinematics (FK) Plot:
  - Displays a 3D plot of the robot arm's current configuration using IKPy and Matplotlib.
  - Automatically updates when sliders are adjusted or during autonomous operations.
  - Use Case: Offers a visual representation of the arm's state, aiding in precise adjustments and verification of manipulator actions.
- Switch to Autonomous Mode:
  - A toggle button to enable or disable autonomous mode.
  - Transitions from manual control to fully autonomous operations, where the robot navigates and manipulates objects on its own.
  - Use Case: Allows switching between manual and autonomous functionalities, providing flexibility for diverse scenarios.

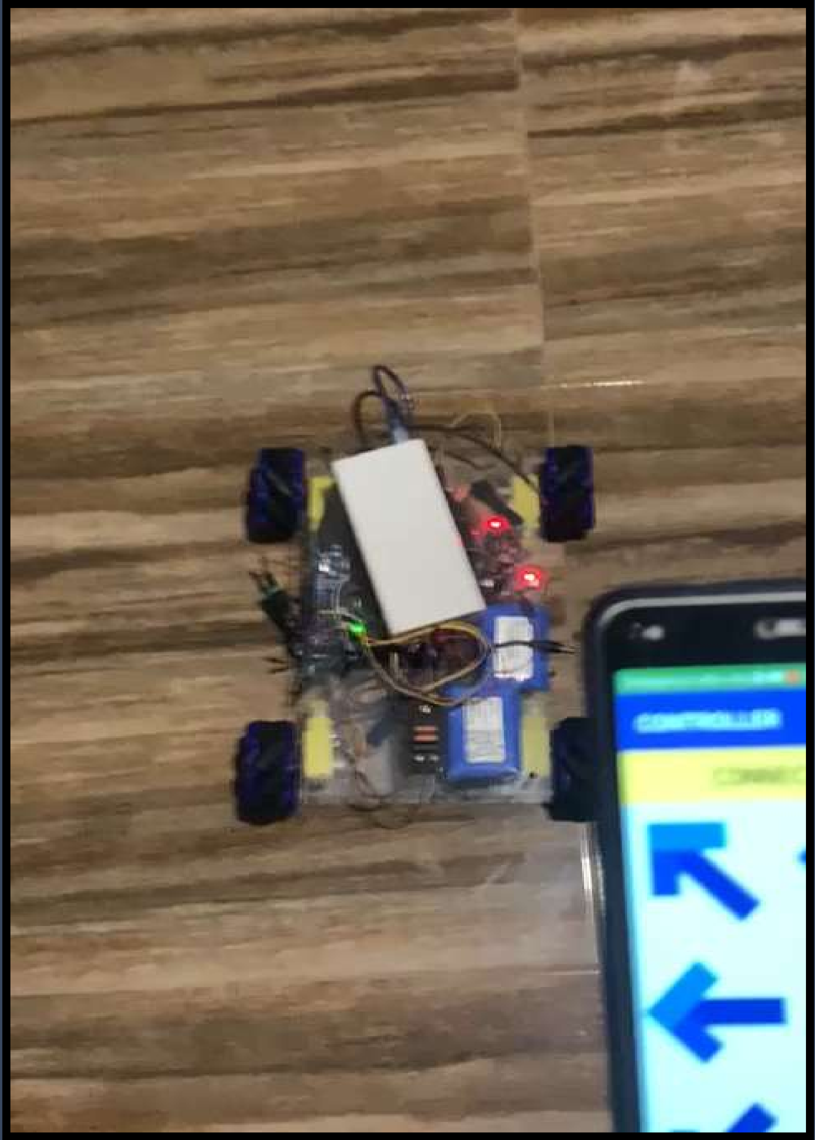
CONTROL SYSTEM – WEB PAGE



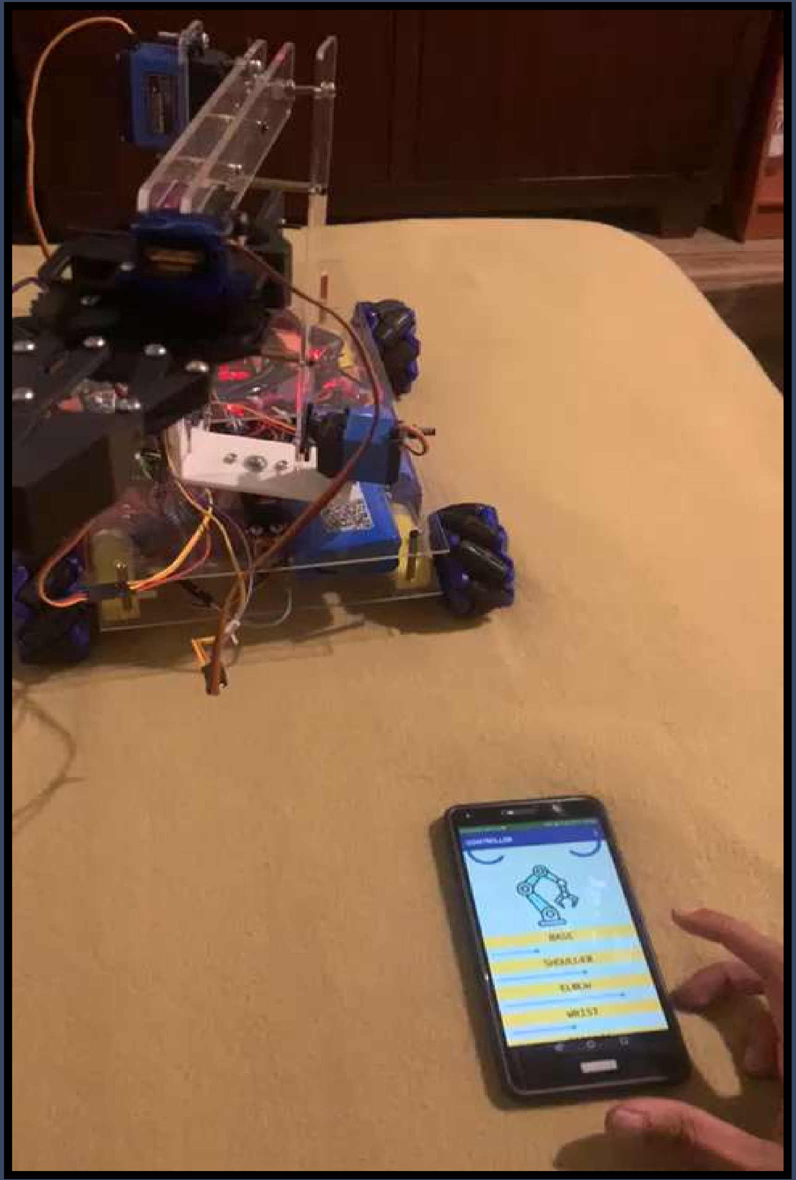
MOBILE APPLICATION

MOBILE APPLICATION CONTROLLING





MOBILE APPLICATION CONTROLLING



ERRORS ENCOUNTERED

1. **Fabrication Misalignments**:
   1. Slight inaccuracies during assembly caused **imperfect alignment** of the chassis, which negatively affected the performance of the **mecanum wheels**.
   2. Resulted in **inefficient omnidirectional movement** due to suboptimal contact between wheels and the surface.
2. **Heavy Chassis Design**:
   1. The increased weight of the chassis led to **uneven weight distribution**, further reducing the ideal traction required for the mecanum wheels to function properly.
   2. Affected smooth and precise movement, especially during rotations or transitions between directions.
3. **Inconsistent Current Draw from Motors**:
   1. **Soldering and wiring inconsistencies** caused variations in current drawn by the motors, leading to uneven motor speeds.
   2. Resulted in unpredictable behavior during manual and autonomous movement, especially during fine maneuvers.

LIMITATIONS

- Camera Calibration Issues:
  - Limited calibration accuracy affected the depth estimation and real-world coordinate mapping.
  - Reduced the precision of object detection and manipulator positioning.
- Low Processing Power of Raspberry Pi:
  - The limited computational capacity of the Raspberry Pi led to slower processing of real-time image data.
  - Contributed to a delay in decision-making during autonomous operations.
- Low FPS (Frames Per Second):
  - The low FPS from the camera resulted in slower response times for object detection and navigation.
  - Made the robot less effective in dynamic environments with fast-moving objects or obstacles.

KEY TAKEAWAYS

- Fabrication and electrical inconsistencies need to be addressed for better mechanical and electrical reliability.
- Upgrading hardware like the Raspberry Pi to a more powerful controller (e.g., NVIDIA Jetson or equivalent) can improve processing power and FPS.
- Enhanced calibration techniques or using a depth sensor and lighter chassis materials could significantly improve system performance.