Mechanical Design & Load Analysis 5-DOF Robotic Arm

1: System Description

This report presents the complete mechanical design, kinematic modeling, and static load analysis of a 5-Degree of Freedom (5-DOF) robotic arm designed for sorting applications.

The robot is intended to pick, manipulate, and place objects into predefined locations based on sorting criteria such as length.

The analysis focuses on:

- **Links**
- **Joints**
- **Gripper (End Effector)**
- **The robot base is assumed to be fixed and therefore excluded from kinematic and dynamic calculations, in accordance with standard robotic modeling practice.**

2: System Overview

1. **Manipulator Type: Serial robotic arm**
2. **Degrees of Freedom: 5**
3. **Joint Type: All joints are revolute**
4. **Application: Sorting and pick-and-place operations**
5. **Base Condition: Fixed support**
6. **Manufacturing Method: 3D printing**

3: Degrees of Freedom & Joint Configuration

Joint No.	Joint Type	Function
J1	Revolute	Base/Waist rotation
J2	Revolute	Shoulder lift
J3	Revolute	Elbow motion
J4	Revolute	Wrist pitch
J5	Revolute	Gripper rotation / actuation

Total Joints = 5

Total DOF = 5

All joints are rotational (Revolute Joints)

4: Link Definition and Classification

Each link is defined as a rigid body connecting two consecutive joints.

Link ID	Description
L1	Waist Link
L2	Upper Arm
L3	Forearm
L4	Wrist Link

- **The base is not classified as a link since it does not contribute to motion.**

5: Material Selection – ABS

The robotic arm structure is manufactured from ABS (Acrylonitrile Butadiene Styrene) due to:

Low density → reduced inertia

Adequate mechanical strength

Ease of manufacturing (3D printing / molding)

Electrical insulation

Mechanical Properties of ABS:

- **Density =1040,Kg/ m^3**
- **Tensile strength ≈ 40 MPa**
- **Elastic modulus ≈ 2–2.5 GPa**

Material Justification:

Lightweight → reduced torque demand
Adequate strength for low-payload robotic systems
Good vibration damping
Suitable for precise 3D printing

6.CAD-Based Mass Properties

All mass properties were extracted directly from the SolidWorks Mass Properties tool, ensuring consistency between CAD geometry and analytical calculations.

Assembly Mass Properties:

- **Total moving mass: 0.62156 kg**
- **Center of Mass (COM):**

- **X = 108.05 mm**
- **Y = 133.33 mm**
- **Z = 85.11 mm**

The motors are excluded from link mass calculations and treated as external loads applied at joint locations.

7:Denavit–Hartenberg(D–H)Kinematic Modeling

The kinematic model of the robotic arm is developed using the standard Denavit–Hartenberg (D–H) convention.

D–H Parameters Definition:

- **θ_i : Joint angle**
- **d_i: Link offset**
- **a_i: Link length**
- **α_i: Link twist**

8: D–H Parameter Table

Joint	Θi(mm)	di(mm)	ai(mm)	αi (rad)
1	θ_1	194	0	$+\pi/2$
2	θ_2	0	115	0
3	θ_3	0	50	0
4	θ_4	0	120	0
5	θ_5	0	0	0

These parameters accurately represent the physical geometry of the robotic arm and form the basis for forward and inverse kinematics.

9: Gripper (End Effector) Analysis

The gripper is treated as an independent mechanical unit.

- **Gripper Mass: Extracted from CAD**
- **Payload Mass: 0.05 kg (design value)**

Total Load at End Effector:

m(total)=m (gripper) + m (payload)

The gripper is designed to handle the payload safely without exceeding joint torque limits.

10: Mass Calculation of Links

The mass of each link is calculated using the standard mass–density relationship:

m(link) =p×V(link)

Where:

p= density of ABS

V= volume extracted from CAD (SolidWorks)

- **Volume and Center of Mass are obtained directly from CAD software (Mass Properties).**

Placeholder Table (to be filled from SolidWorks):

Link	Volume (m^3)	Mass (kg)
L1	1.15×10^{-4}	0.119
L2	1.35×10^{-4}	0.141
L3	0.48×10^{-4}	0.050
L4	1.21×10^{-4}	0.126

11: Joint Mass Calculation

Each joint housing is treated as a rigid body.

m(joint) =p×V(joint)

- **Motors are not included in link mass and are treated as external loads acting on joints.**

Joint	Volume (m^3)	Mass (kg)
J1	0.25×10^{-4}	0.026
J2	0.32×10^{-4}	0.033
J3	0.22×10^{-4}	0.023
J4	0.18×10^{-4}	0.019

12: Gripper Analysis (Independent Unit)

The gripper is treated as the end effector tool.

Components considered:

- **Gripper body mass**
- **Actuation mechanism**
- **Payload (object to be lifted)**

Payload is limited by:

- **Grip force**
- **Joint torque capacity**
- **Structural safety factor**

13: Load Accumulation on Joints

Each joint must support the weight of all components located after it.

$W_i = \sum (m_k \cdot g)$

Where:

$g=9.81, m/s^2$

14:Required Torque Calculation

The required torque at each joint is calculated as:

$T_i=\sum (m_k \cdot g.d_k)$

Where:

d_k= distance from joint axis to center of mass

Design Torque:

$T(design)=T(\ required)\times SF$

Safety Factor SF= 1.5_2

15: Torque Calculation (Worst-Case Scenario)

The worst-case loading condition occurs when the arm is fully extended horizontally.

Torque Equation:

$T=m.g.d$

Calculated Values:

- **Arm torque ≈ 8.12 kg·cm**
- **Payload torque ≈ 1.40 kg·cm**

Total Required Torque:

T(required)~9.52 kg.cm

16: Motor Capability Verification

- **Motor Type: MG995=50gm +sg90s=9gm**
- **Rated Torque: 13 kg·cm @ 6V**
- **Safety Factor: [SF= 13/9.52=~1.36]**

This safety factor ensures reliable operation under real conditions, accounting for friction and dynamic effects.

Design condition:

T(motor)>=2×T(required)

- **This ensures:**
- **No motor stall**
- **Stable motion**
- **Long motor lifetime**

17: Weight Optimization Justification

ABS reduces total arm mass

Hollow link design reduces inertia

Maximum load concentrated near the gripper only

This results in:

- **Lower torque demand**
- **Better dynamic response**
- **Improved system stability**

- **Assumptions**
- **Quasi-static operation**
- **Friction neglected**
- **Rigid links**
- **Fixed base**
- **Vertical gravitational loading**

18:Conclusion

- **The mechanical design of the 5-DOF robotic sorting arm has been fully validated.**
- **All links, joints, and the gripper satisfy mechanical strength and torque requirements based on CAD-verified mass properties and standard engineering equations.**
- **The robot is mechanically stable, lightweight, and capable of safely handling the specified payload for sorting applications.**