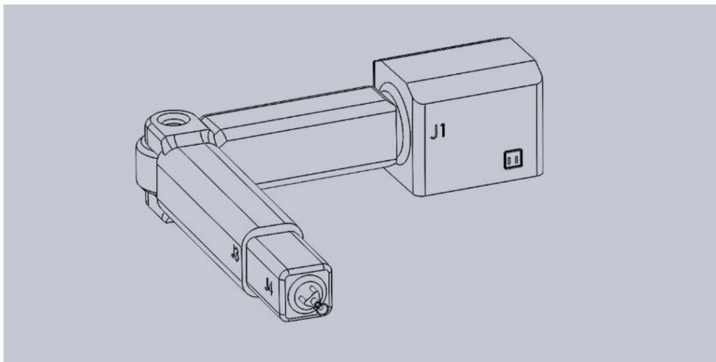
INTRODUCCION TO ROBOTICS.

Why we design this robot?

The BATT-BOT was designed to be an affordable solution for industrial automation, especially for small and medium-sized businesses looking to streamline their processes without incurring the high costs of traditional industrial robots.



Reasons for Low Cost:

1. **Simplified Design:**
   - Focuses on performing specific tasks such as assembling batteries, eliminating complex and unnecessary functions for its purpose. This reduces both material and manufacturing costs.
2. **Use of Economical Components:**
   - Built with standard materials and parts that are accessible on the market, without sacrificing quality or durability.
3. **Scalable Production:**
   - Its modular design allows for mass production at a lower cost.
4. **Ease of Maintenance:**
   - Components are easy to repair or replace, significantly reducing long-term operating expenses.
5. **Energy Efficiency:**
   - Designed to consume less energy compared to other larger and more sophisticated industrial robots.

Benefit for Industry

The low cost makes the BATT-BOT an ideal choice for companies that:

- Want to adopt automation for the first time.
- Need cost-effective solutions to compete in the global market.
- Are looking for a quick return on investment (ROI) by reducing operating costs and improving efficiency.

Mathematical Model of the Robot

The mathematical model of a robotic arm consists of two main components:

1. **Kinematics**: Describes how the end-effector's position and orientation depend on the joint angles.
2. **Dynamics**: Calculates the forces and torques required to move the joints, considering the physical properties of the robot.

1. Kinematics

1.1. Denavit-Hartenberg (DH) Parameters

Using the DH convention,

Link	θ (rad)	d (mm)	a (mm)	α (rad)	Joint Type
1	0	0	35	0	Rotational
2	0	0	40	0	Rotational
3	0	0	0	0	Prismatic
4	0	0	15	0	Rotational

1.2. Homogeneous Transformation Matrix

The transformation matrix for each link is given by:

$$T_i^i + 1 = \begin{bmatrix} \cos\theta_i & -\sin\theta_i\cos\alpha_i & \sin\theta_i\sin\alpha_i & a_i\cos\theta_i \\ \sin\theta_i & \cos\theta_i\cos\alpha_i & -\cos\theta_i\sin\alpha_i & a_i\sin\theta_i \\ 0 & \sin\alpha_i & \cos\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Step 1: T_0^1

For the first link:

- $\theta_1 = 0, d_1 = 0, a_1 = 35, \alpha_1 = 0$

$$T_0^1 = \begin{bmatrix} 1 & 0 & 0 & 35 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Step 2: T_1^2

For the second link:

- $\theta_2 = 0, d_2 = 0, a_2 = 40, \alpha_2 = 0$

$$T_1^2 = \begin{bmatrix} 1 & 0 & 0 & 40 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Step 3: T_2^3

For the third link

- $\theta_3 = 0, d_3 = d_3$ (prismático), $a_3 = 0, \alpha_3 = 0$

$$T_2^3 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & d_3 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Step 4: T_3^4

For the fourth link:

- $\theta_4 = 0, d_4 = 0, a_4 = 15, \alpha_4 = 0$

$$T_3^4 = \begin{bmatrix} 1 & 0 & 0 & 15 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Final Transformation

The total transformation T_0^4 is obtained by multiplying the matrices:

$$T_0^4 = T_0^1 \cdot T_1^2 \cdot T_2^3 \cdot T_3^4$$

The total homogeneous transformation matrix, considering $d3$=0

$$T_0^4 = \begin{bmatrix} 1 & 0 & 0 & 90 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

This means that the final position is **at x = 90 mm, y = 0, z = 0** in space, relative to the base coordinate system.

2. Dynamics

The dynamics of the robot describe how forces and torques are generated in response to desired motion, considering the robot's physical properties. These dynamics are typically represented using the Euler-Lagrange equation:

$$\tau = M(q)\ddot{q} + C(q, \dot{q})\dot{q} + G(q)$$

Where:

- τ: Vector of joint torques/forces.
- $\mathbf{M}(\mathbf{q})$: Inertia matrix.
- $\mathbf{C}(\mathbf{q}, \dot{\mathbf{q}})\dot{\mathbf{q}}$: Coriolis and centrifugal forces.
- $\mathbf{G}(\mathbf{q})$: Gravitational forces.
- $\mathbf{q}$: Vector of joint variables (angles for rotational joints, displacements for prismatic joints).
- $\dot{\mathbf{q}}$: Joint velocities.
- $\ddot{\mathbf{q}}$: Joint accelerations.

2.1. Inertia Matrix M(q)

The inertia matrix represents how the masses of the links affect the robot's movement:

$$M(q) = \begin{bmatrix} I_1 + I_2 + I_3 + I_4 & 0 & 0 & 0 \\ 0 & I_2 + I_3 + I_4 & 0 & 0 \\ 0 & 0 & I_3 + I_4 & 0 \\ 0 & 0 & 0 & I_4 \end{bmatrix}$$

Where:

- $I_i = \frac{1}{3} m_i L_i^2$: Moment of inertia of link i.
- m_i: Mass of link i.
- L_i: Length of link i.

2.2. Coriolis Matrix C ($q, \dot{q}$)

The Coriolis matrix contains terms that account for interactions between joint velocities:

$$C(q,\dot{q}) = \begin{bmatrix} 0 & -c_{12}\dot{q}_2 & -c_{13}\dot{q}_3 & -c_{14}\dot{q}_4 \\ c_{12}\dot{q}_1 & 0 & -c_{23}\dot{q}_3 & -c_{24}\dot{q}_4 \\ c_{13}\dot{q}_1 & c_{23}\dot{q}_2 & 0 & -c_{34}\dot{q}_4 \\ c_{14}\dot{q}_1 & c_{24}\dot{q}_2 & c_{34}\dot{q}_3 & 0 \end{bmatrix}$$

The coefficients $\mathbf{c_{ij}}$ depend on the robot's configuration and physical properties.

2.3. Gravitational Terms G(q)

The gravitational vector represents the torques needed to counteract gravity:

$$G(q) = \begin{bmatrix} m_1 g \frac{L_1}{2} \\ m_2 g \frac{L_2}{2} \\ m_3 g \frac{L_3}{2} + m_{\text{load}} g L_3 \\ m_4 g \frac{L_4}{2} + m_{\text{load}} g L_4 \end{bmatrix}$$

Summary of the Mathematical Model

1. **Forward Kinematics:**

$$T_0^4 = T_0^1 \cdot T_1^2 \cdot T_2^3 \cdot T_3^4$$

• The end-effector's position is expressed as (x, y, z) in terms of the joint angles.

2. **Dynamic Equation:**

$$\tau = M(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q)$$

Where:

- M(q) Inertia matriz.
- C (q, $\dot{q}$) Coriolis terms.
- G(q): Gravitational terms

1. **Introduction:**
   "We have modeled the dynamics of a 4-link robot manipulator using the Euler-Lagrange approach. The key components include the Inertia Matrix, Coriolis Matrix, and Gravitational Terms."
2. **Explain Each Component:**
   - **Inertia Matrix:** "The inertia matrix $M(q)$ shows how the masses and moments of inertia of the links resist accelerations at each joint."
   - **Coriolis Matrix:** "The Coriolis matrix $C(q, \dot{q})$ accounts for the effects of joint velocities interacting with each other."
   - **Gravitational Terms:** "The gravitational vector $G(q)$ represents the torques needed to hold the robot against gravity."
3. **Results:**
   - Show the **output matrices** and explain their significance.
   - Highlight that the calculated matrices are critical for trajectory planning and control.
4. **Conclusion:**
   "These dynamic equations form the foundation for calculating the forces and torques needed to move the robot accurately and efficiently."

Robot Features

Parameter	Value
Length of Link 1	L_1=35cm (0.35 m)
Length of Link 2	L_2=40cm (0.40 m)
Length of Link 3	L_3=15cm (0.15 m)
Mass of Robot Body	m=1.5kg (link 1)
	m=1.2kg (link 2)
	m=0.8kg (link 3)
Mass of the Load	m_{load}=0.5kg
Maximum Angular Acceleration	α=1rad/s
Maximum Angular Velocity	ω=1.77rad/s
Gravitational Force	g=9.81m/s2
Maximum Torque	Calculated for each joint
Maximum Required Power	Calculated for each joint

Calculate Torque and Power for each joint

```
Specifications of motors for each joint:
Joint 1:
  Maximum Torque: 0.06 Nm
  Required Power: 0.11 W
Joint 2:
  Maximum Torque: 2.42 Nm
  Required Power: 4.28 W
Joint 3:
  Maximum Torque: 0.59 Nm
  Required Power: 1.05 W
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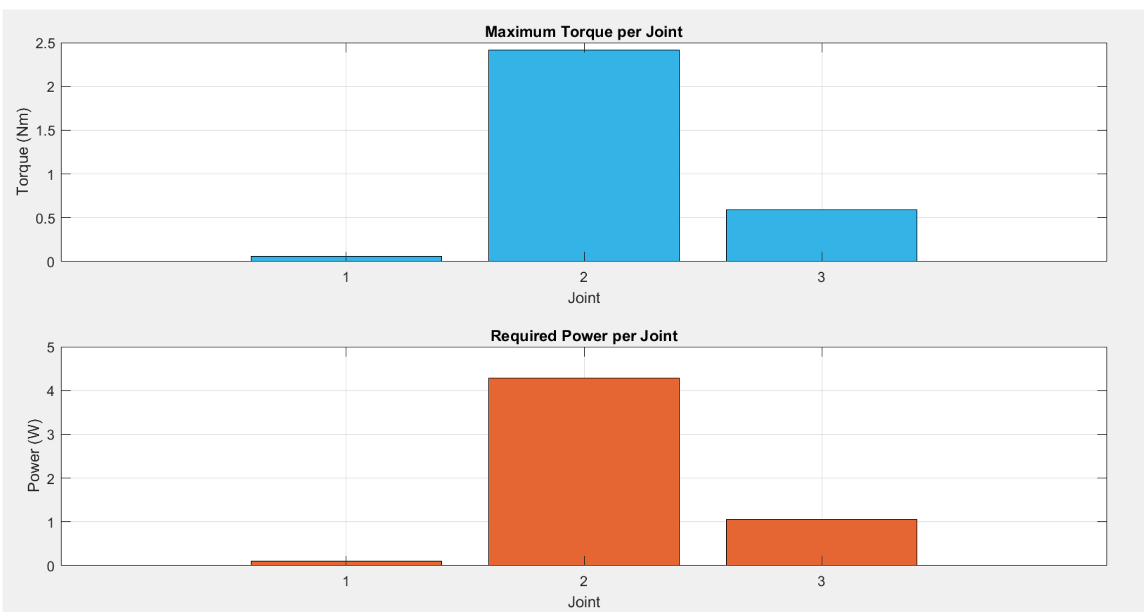

Motor specifications

Motors Recommendations

JOINT 1

- Required torque: τ_1 = 0.96 Nm
- Required power: P_1 = 1.70 W

Recommendation:

- **Motor:** Pololu 37D DC Gearmotor 19:1
- **Continuous torque:** 1.6 Nm (sufficient for safety factor).
- **No-load speed:** 320 rpm (33.5 rad/s, easily adjustable with PWM control).
- **Power:** 6 W

https://en.zd-motor.com/?gad_source=1&gclid=CjwKCAiA9vS6BhA9EiwAJpnXw2qV0rzX4A10thsTyhqliCJiXpZHWYADSOfltQ3CwUVH75tW5qvlHBoCi4QQAvD_BwE

JOINT 2

- Required torque: τ_2=1.01 Nm
- Required power: P_2=1.78 W

Recommendation:

- **Motor:** NEMA 17 Stepper Motor (with 5:1 gearbox)
- **Continuous torque:** 1.8 Nm (sufficient with margin).
- **Speed:** Supports 1.77 rad/s when using a suitable controller.
- **Power:** 8 W (more than enough).

https://www.wanzhida.com/product/product_7.html?gad_source=1&gclid=CjwKCAiA9vS6BhA9EiwAJpnXw7JgBB0R8kdLHw2hEyEOg3MtLrdpONGUjRbbZ807PXvtgIui83f5HhoCM8MQAvD_BwE

JOINT 3

- Torque required: $\tau_3 = 0.09$
- Power required: $P_3 = 0.17$ W

Recommendation:

- **Motor:** MG90S Servo Motor
- **Continuous torque:** 0.18 Nm (twice the required torque).
- **Speed:** 0.1 s/60° (equivalent to 10 rad/s).
- **Power:** 1 W (well above the requirement).

https://www.icshop.com.tw/products/368060200007?gad_source=1&gclid=CjwKCAiA9vS6BhA9EiwAJpnXw2BhT4PUu5lsrdlO434IjyG4iqKatlFR_zlOvMtwcD20dJj3xS288hoCHJIQAvD_BwE

Motor Specifications and Comparison:

Joint	Required_Torque_Nm	Motor_Torque_Nm	Required_Power_W	Motor_Power_W
1	0.96	1.6	1.7	6
2	1.01	1.8	1.78	8
3	0.09	0.18	0.17	1

- **Introduction**: "Here, we analyze the required torque and power for each joint of the robot and compare them with the specifications of the selected motors."
- **Table**: "The table shows that for each joint, the selected motors provide higher torque and power than what is required. This ensures the motors operate well below their limits, providing reliability and durability."
- **Torque Comparison Plot**: "In the first plot, we can see that the torque provided by the motors (blue bars) exceeds the required torque (orange bars). This confirms that the motors are capable of handling the load under all conditions."
- **Power Comparison Plot**: "In the second plot, the motor power (blue bars) is significantly higher than the required power (orange bars). This provides a safety margin to avoid motor overheating or power failure."
- **Conclusion**: "The selected motors are well-suited for our robot. They meet the torque and power requirements with sufficient margins, ensuring efficient and reliable performance."

Analysis of the PID Simulation Results

Graph 1: Joint Positions

1. Objective:
    - Move the robot joints from their initial positions ($q_{\text{init}} = 0$) to the desired positions ($\pi/4, \pi/6, \pi/3$).
2. **Observations**:
    - The **joint responses** show smooth and stable convergence to the desired positions.
    - **Joint 3** (blue line) reaches its target position faster due to the higher initial torque applied.
    - **Joints 1 and 2** (red and green lines) also converge to their targets, but take slightly longer.
3. **PID Controller Behavior**:
    - The **proportional term (K_p)** reduces the position error quickly.
    - The **derivative term (K_d)** smooths the response, preventing large oscillations.
    - The **integral term (K_i)** eliminates residual errors, ensuring that the final joint positions match the desired values.

Graph 2: Joint Torques

1. **Objective**:
   - Display the torques calculated by the PID controller to move the joints to their desired positions.
2. **Observations**:
   - The **initial torques** are high (around $50\,\mathrm{Nm}$) because the initial error between the current and desired positions is significant.
   - As the joints approach their target positions, the torques **decrease to zero**, indicating that the system has reached equilibrium.
   - The torque applied is **smooth and stable**, demonstrating the effectiveness of the PID controller in avoiding excessive oscillations.
3. **Significance**:
   - Stable torques are critical for minimizing unnecessary stress on the motors and ensuring precise, controlled movement of the robot.

Model of BATT-BOT SERIES (S M L)

1. BATT-BOT S (Small)

Application: Ideal for ultra-compact assembly tasks, focusing on small and lightweight components.

Specifications:

- **Link Dimensions:**
  - L1: 25 cm (0.25 m)
  - L2: 30 cm (0.30 m)
  - L3: 10 cm (0.10 m)
- **Horizontal Reach:** 65 cm (0.65 m).
- **Maximum Payload:** 0.3 kg.
- **Accuracy (Repeatability):** ±0.05 mm.
- **Maximum Angular Speed (ω):** 1.5 rad/s.
- **Total Robot Weight:** 4 kg.
- **Power Required:** <80 W.
- **Applications:** Assembly of small batteries, connectors, and lightweight electronic components.

2. BATT-BOT M (Medium)

Application: Designed for standard production lines, handling assembly tasks with extended reach and medium payloads.

Specifications:

- **Link Dimensions:**
  - L1: 35 cm (0.35 m)
  - L2: 40 cm (0.40 m)
  - L3: 15 cm (0.15 m)
- **Horizontal Reach:** 90 cm (0.90 m).
- **Maximum Payload:** 0.5 kg.
- **Accuracy (Repeatability):** ±0.03 mm.
- **Maximum Angular Speed (ω):** 1.77 rad/s.
- **Total Robot Weight:** 6.5 kg.
- **Power Required:** <100 W.
- **Applications:** Standard battery assembly, handling cells and small electronic device modules.

3. BATT-BOT L (Large)

Application: Optimized for assembly on larger production lines, with greater reach and payload capacity.

Specifications:

- Link Dimensions:
  - L1: 50 cm (0.50 m)
  - L2: 60 cm (0.60 m)
  - L3: 20 cm (0.20 m)
- **Horizontal Reach:** 130 cm (1.30 m).
- **Maximum Payload:** 1.0 kg.
- **Accuracy (Repeatability):** ±0.02 mm.
- **Maximum Angular Speed (ω):** 2.0 rad/s.
- **Total Robot Weight:** 10 kg.
- **Power Required:** <150 W.
- **Applications:** Assembly of large modules, assembly on more demanding lines, handling of heavier cells.

Comparison in Table:

Model	Horizontal Reach (m)	Maximum load (kg)	Precisions (mm)	Peso Total (kg)	Potency (W)
BATT-BOT S	0.65	0.3	±0.05	4	<80
BATT-BOT M	0.90	0.5	±0.03	6.5	<100
BATT-BOT L	1.30	1.0	±0.02	10	<150

Advantages of Having Three Models:

1. Flexibility: They adapt to different production needs.

2. Scalability: They allow companies to grow without changing technology.

3. Cost-Efficiency: Each model is optimized for its specific use, saving unnecessary costs.