ReConArm

A 3R+P Configuration to Mitigate Singularities in Robotic Welding

Intro to Robotics Final Project
Group 1

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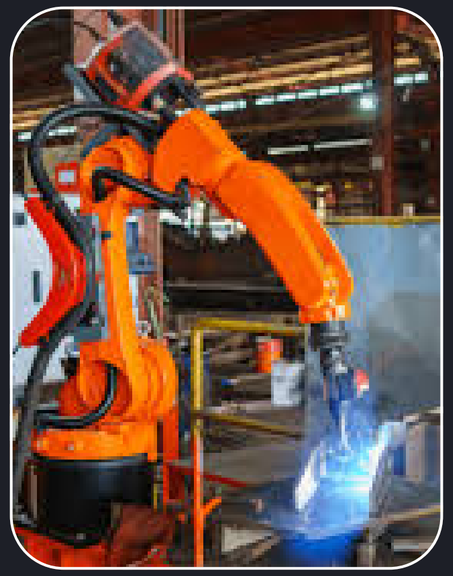
Problem & Motivation

In robotic arc welding, 3R serial structures are widely used for positioning the torch near the weld seam.
Conventional 3R positioning configurations suffer from kinematic singularities (e.g., elbow/shoulder alignment), causing:



- Loss of effective DOF and poor controllability
- Motion interruptions or erratic joint speeds
- Difficulties tracking long, smooth weld paths

Our problem: Can we modify existing 3R configuration to reduce the practical impact of these singularities and extend the reachable weld region without completely redesigning industrial arms?

Prior Approaches to solving problem

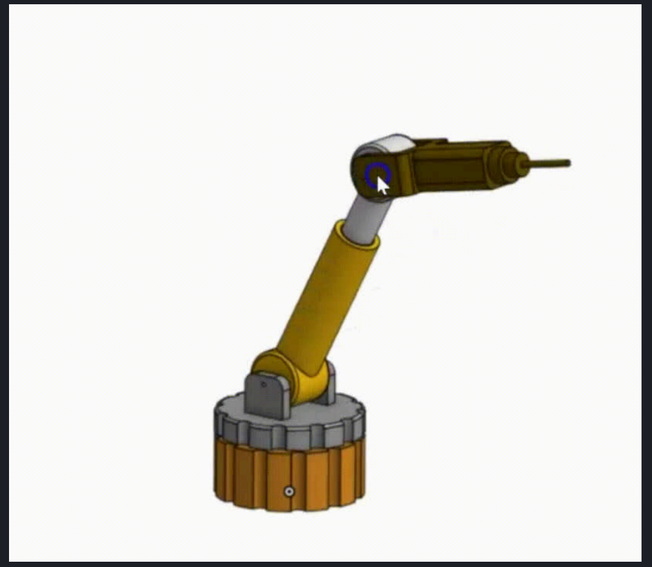
- Kinematic Redundancy & Redundancy resolution
- Variable-geometry manipulators (telescoping links).
- Path planning algorithms to bypass singular regions

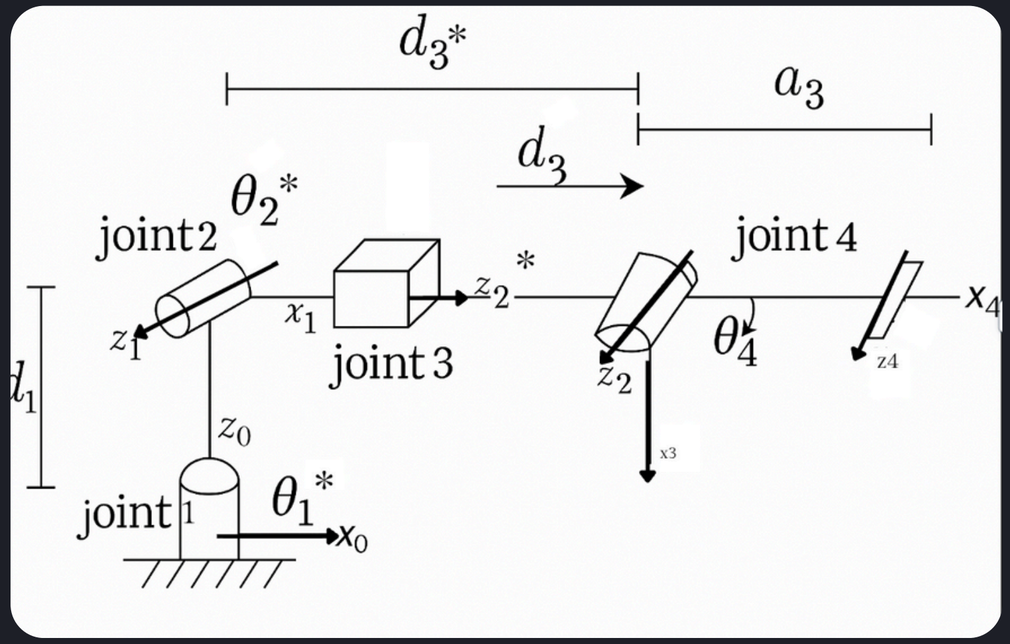
Gap: Less attention to minimal structural modifications to a 3R chain specifically for welding-style paths.

Solution Approach

- Introduce a 3R+P design by replacing the third revolute joint with a prismatic link to avoid elbow-shoulder singularities.
- Build the full kinematic model with frames, DH table, forward kinematics, and Jacobian to study singularity behavior.
- Develop a closed-form IK for position with a fixed wrist plane to generate smooth weld trajectories.
- Simulate the arm with Lagrange-Euler dynamics to evaluate joint motion during welding.
- Compare workspace and singularity regions against a standard 3R arm to measure performance improvements.

Joint	a_i	α_i	d_i	θ_i
1	0	$\frac{\pi}{2}$	d_1	θ_1^*
2	0	$\frac{\pi}{2}$	0	θ_2^*
3	0	$\frac{\pi}{2}$	d_3^*	π
4	a_3	0	0	θ_4^*





Results (IK, Trajectory, Dynamics)

- Inverse Kinematics: derived a closed-form IK for position-only with fixed “wrist plane” orientation
  - Inputs: (x,y,z) and θ24
  - Unknowns: θ1, θ2, , d3, θ4

$$\boxed{\theta_1 = \arctan(-P_y, -P_x)}$$

$$R = a_3\,C_4 - d_3\,S_2 = -(P_x C_1 + P_y S_1)$$

$$P_z = d_1 - a_3\,S_4 - d_3\,C_2$$

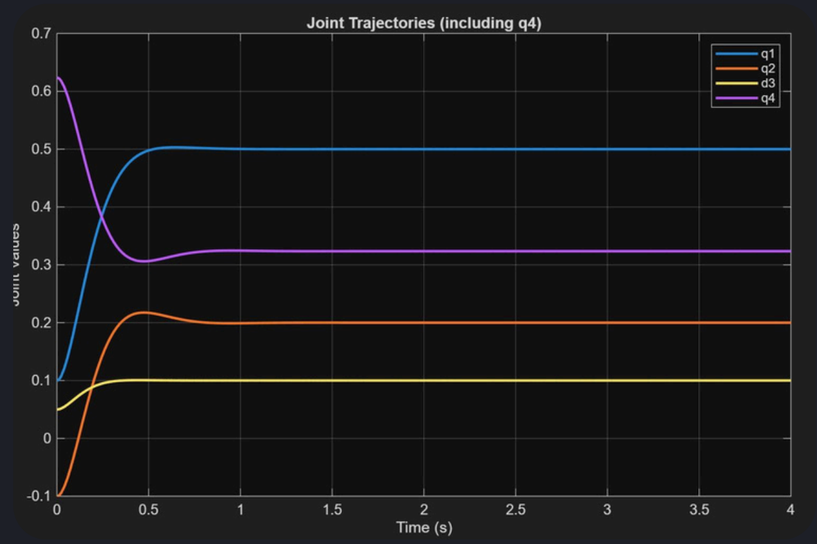
$$N = d_3\,S_2 = a_3 C_4 + P_x C_1 + P_y S_1$$

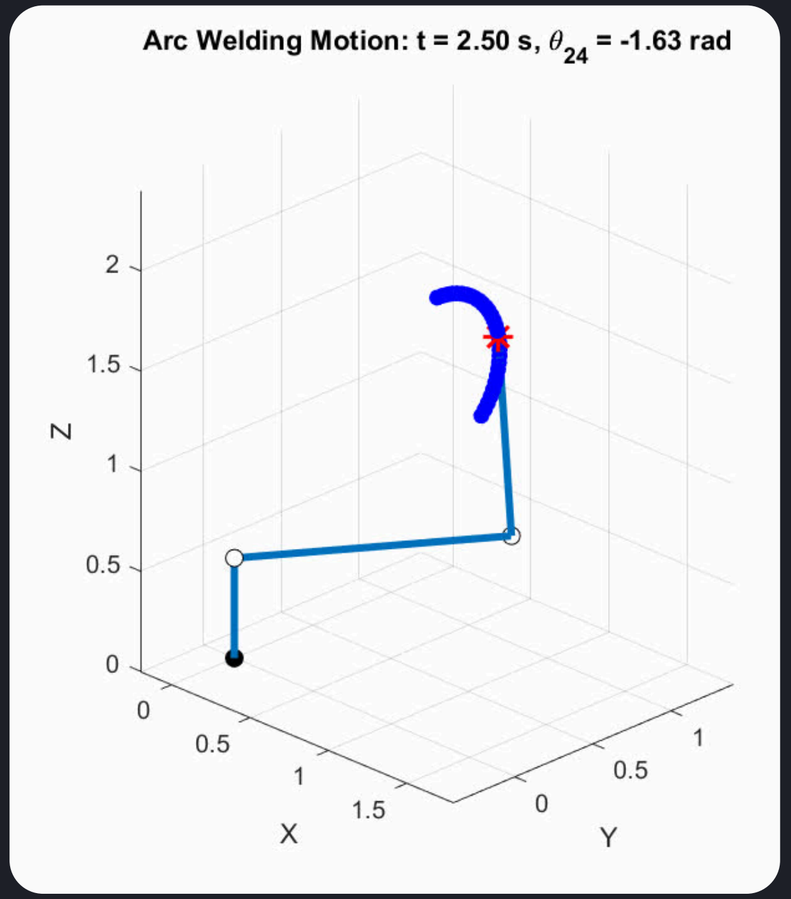
$$C = d_3\,C_2 = d_1 - a_3 S_4 - P_z$$

$$\Longrightarrow \boxed{d_3 = \pm\sqrt{N^2 + C^2}}$$

$$\boxed{\theta_2 = \arctan(N, C)}$$

$$\boxed{\theta_4 = \theta_{24} - \theta_2}$$

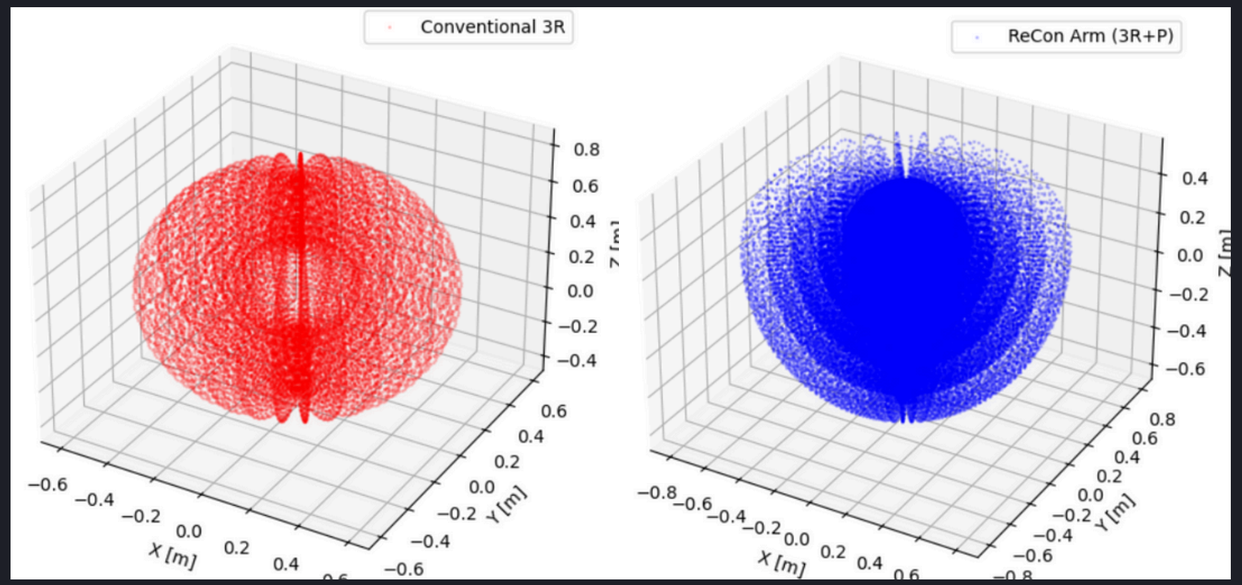




- Dynamics: Modeled ReCon Arm dynamics using Lagrange—Euler formulation and PD controller.

Results (Workspace & Singularities)

- We do a comparison of the reachable workspace of a conventional 3R configuration and ReConArm of identical parameters



- Using the DH table, the jacobian was calculated to explore the following singularity regions:
  - Full: Total loss of end-effector control
  - Position: Motion Restricted
  - Orientation: Wrist Lock

- ReConArm replaces the unavoidable 3R elbow singularity with a controllable d3=0 singularity, making the system more navigable.

- Wrist-plane orientation singularities remain, but are now avoidable, unlike for a conventional 3R robot.

$$J_{6\times4} = \begin{bmatrix} -s_1(d_3s_2 - a_3c_{24}) & (a_3s_{24} + c_2d_3)c_1 & c_1s_2 & a_3c_1s_{24} \\ c_1(d_3s_2 - a_3c_{24}) & (a_3s_{24} + c_2d_3)s_1 & s_1s_2 & a_3s_1s_{24} \\ 0 & (d_3s_2 - a_3c_{24}) & -c_2 & -a_3c_{24} \\ 0 & s_1 & 0 & s_1 \\ 0 & -c_1 & 0 & -c_1 \\ 1 & 0 & 0 & 0 \end{bmatrix}$$

Singularity Type	Condition
Full Jacobian Singularity	$d_3 = 0$
Position (Translational) Singularity	$a_3\cos(\theta_2 + \theta_4) = d_3\sin\theta_2$
Orientation (Rotational) Singularity	$\theta_4 = k\pi, \quad k \in \mathbb{Z}$

Conclusions

ReConArm reduces the severity and frequency of classical 3R welding singularities through a minimal structural modification.
The added prismatic joint expands the practical workspace and improves controllability along smooth weld trajectories.
Analytic kinematics and dynamic simulation confirm that the 3R+P configuration provides more stable motion near critical welding orientations.

Future Extensions

- Extend the IK to full orientation control for complete 6DoF weld-path tracking.
- Include torque limits, friction, and actuator models to better reflect real welding dynamics.
- Add redundancy resolution and real-time singularity-avoidance control to enhance the 3R+P design.
- Integrate automated path-planning to measure weld-coverage improvements.
- Build a physical ReConArm prototype to test weld-trajectory smoothness with feedback control.

Questions & Answers