Robotic Welding Arm Simulation - Project Report

Abstract

This project presents the design, simulation, and control of a six degrees-of-freedom (6-DOF) robotic welding arm tailored for motorcycle headstock manufacturing. The goal of this work was to simulate the robotic manipulator's complete operational pipeline, from spatial modeling and path planning to kinematic and dynamic analysis. The simulation was conducted in MATLAB and Simulink, with a structured approach over four phases: application definition, kinematics modeling, obstacle-aware path planning, and dynamic control implementation. The workspace was defined with specific constraints, and the robot was required to reach three designated weld points while avoiding static obstacles. This project leverages analytical and numerical techniques to create a framework suitable for deployment in smart manufacturing cells, where automation, accuracy, and reliability are paramount. CAD models were used to visualize spatial constraints and robot geometry. The outcome of the project includes validated control simulations, optimal trajectories, and torque profiles, all designed for real-time robotic execution.

Problem Statement

The welding of a motorcycle headstock requires precise alignment, consistent motion, and collision-free workspace navigation. Traditional manual welding methods face challenges such as inconsistencies in joint quality, human fatigue, and inefficiency. This project proposes an automated solution by simulating a robotic arm designed specifically to perform welding tasks in a defined environment. The robotic system must reach three key weld points within a 3D workspace measuring approximately 2.75m in length, 0.1m in width, and 2.25m in height. The arm must operate within these constraints while accounting for fixed obstacles, such as fixtures and surrounding equipment. The environment also includes a rotating fixture to support the workpiece. The robot's end-effector, which simulates the welding torch, must traverse a path that aligns with weld seams while avoiding obstruction and ensuring mechanical feasibility. Constraints on joint angles, link lengths, and torque capacities must also be considered throughout the simulation. The project thus aims to build a scalable, modular simulation system that reflects real-world robotics deployment in manufacturing settings.

Methodology

The methodology is divided into four sequential phases as prescribed by the course ECE 9053A:

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1. Application and Workspace Modeling:

The first phase involved selecting the appropriate robotic application and defining the environment. MIG welding of motorcycle headstocks was chosen due to its industry relevance. A six-joint robot with five revolute joints and one prismatic component was selected. The workspace was modeled to include weld zones, a base mount, a rotating fixture, and static boundaries.

2. Kinematic Modeling:

In phase two, Denavit-Hartenberg (DH) parameters were derived to represent joint-to-joint transformations. Forward kinematics were implemented to calculate the end-effector pose. Inverse kinematics was solved using MATLAB's optimization tools (fmincon) to determine feasible joint angles to reach the weld points. Differential kinematics was introduced via Jacobian analysis to study velocity propagation and singularity avoidance.

3. Path Planning:

Phase three focused on the implementation of a potential field-based path planning algorithm. The robot was programmed to traverse a path between the defined weld points while avoiding collision with the static obstacles in its workspace. The potential field planner modeled attractive forces toward weld points and repulsive forces away from obstacles, producing smooth trajectories optimized for control feasibility.

4. Dynamics and Control Simulation:

The final phase dealt with modeling the system dynamics using the Euler-Lagrange formulation. Each joint's torque requirement was derived symbolically, then evaluated numerically using MATLAB scripts. Control algorithms were implemented to follow reference trajectories using inverse dynamics. Simulations using ODE45 were carried out to validate system response and torque feasibility.

MATLAB Code Overview

The MATLAB files developed during the project include the following core scripts:

- forwardKinematics.m: Calculates the pose of the robot's end-effector using DH parameters.

- InverseKinematics.m: Numerically solves for joint angles required to reach a target pose.
- DifferntialKinematics.m: Computes the Jacobian matrix to relate joint velocities to end-effector velocities.
- potential_field_path_planning_welding.m: Implements obstacle-aware path planning.
- Dynamic_Equations.m: Derives the equations of motion using symbolic Euler-Lagrange methods.
- InverseDynamics.m: Computes control torque for each joint given the desired trajectory.
- ControlSimulation.m: Simulates closed-loop joint control with torque feedback.
- VerifyInverseForward.m: Cross-validates IK results by recalculating forward kinematics from IK output.

Conclusion and Future Work

This project successfully developed and simulated a robotic welding manipulator for a motorcycle frame. Through a structured approach, the project covered all major aspects of robot control - kinematics, path planning, and dynamics. The solution provides a base framework that could be extended to incorporate real-time controller implementation, hardware-in-the-loop (HIL) testing, and CAD-based collision detection.

Future improvements include:

- Real-time integration with ROS and robotic simulators such as Gazebo.
- Integration of sensor feedback into control algorithms (vision, force, proximity sensors).
- Conversion of symbolic dynamics into optimized C code for embedded deployment.
- Use of reinforcement learning for adaptive path planning.
- Incorporation of digital twin frameworks for real-time monitoring.

Overall, this project lays the foundation for scalable deployment of industrial robots in manufacturing, while enabling data-driven performance monitoring and control accuracy improvements.