Dynamic Spatial Stabilization and Trajectory Tracking of a Spherical Agent on a 6-DOF Robotic Platform

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***Abstract*—This project explores the integration of classical control theory and Reinforcement Learning (RL) to solve the problem of stabilizing a marble on a mobile platform. Using a UR7e 6-axis manipulator, we aim to maintain a marble's position at a target coordinate while the robot undergoes base-level or end-effector trajectories.**

***Index Terms*—ROS 2, Gazebo, LQR, Reinforcement Learning, UR7e, Trajectory Tracking.**

I. Introduction

PRECISION stabilization of unconstrained objects is a fundamental challenge in robotics. This project is different from traditional "Labyrinth" setups because it focuses on Active Surface Control. In this project, the robot must balance a marble on a board or follow a path on a board while also doing a second task, such as following a 3D path with its Endeffector.

II. System Platform and Simulator

For this project, we will utilize:

- **Robot Platform:** Universal Robots UR7e (6-DOF Manipulator).
- **Simulator:** Gazebo Classic 11. This physics-based simulator will provide ground-truth state data for the ball (position/velocity) and simulate the inertial dynamics of the UR7e and the board.
- **Software Stack:** ROS 2 Humble running on Ubuntu 22.04, with MATLAB for State feedback Controller design.

III. Methodology and Learning Component

We propose a hybrid control strategy. An initial state-feedback controller (e.g., LQR) will be designed for baseline stabilization.

Learning Component: We will implement a Reinforcement Learning (RL) agent (using Proximal Policy Optimization or Twin Delayed DDPG) to refine the control policy. The agent will focus on learning the non-linear "residual" dynamics, such as rolling friction and surface-contact perturbations, which are difficult to model analytically.

IV. Project Milestones

The following milestones outline the development trajectory:

A. Milestone 1: Planning and Control (10%)

Focus: Project Proposal + Control Component.

- Derivation of the Nonlinear Model and the linearized State-Space model for the ball-and-plate system.
- **Trajectory Planning:** Development of a path planning module (e.g., quintic polynomials or Spline-based interpolation) to generate smooth, time-parameterized reference trajectories for the marble on the moving board.
- Development of the primary Marble Position Controller (LQR/State-Feedback).
- Implementation of the UR7e Inverse Kinematics (IK) solver in a ROS 2 node.
- Integration of the Robot, Board, and Marble URDF/Xacro into Gazebo with active joint controllers.
- Simulation tests with desired trajectories of the marble on the board.

B. Milestone 2: Learning and Initial Results (10%)

Focus: Presentation + Learning Component.

- Integration of a state observer (Kalman Filter) to handle Gazebo sensor noise and state estimation.
- Setup of the RL training environment (Gymnasium wrapper) for the Gazebo simulation.
- Initial training results showing the RL agent's ability to reduce steady-state error compared to LQR alone.
- Presentation of preliminary results.

C. Milestone 3: Full Project Report and Demo (15%)

Focus: Final Documentation + Full Demo.

- Successful stabilization of the marble at target coordinates while the robot follows a 3D path.
- Comparative analysis between the baseline LQR and the Hybrid LQR+RL policy.
- Submission of a full IEEE-format technical report and final code repository.
- Demo videos showing the system resisting external manual perturbations in Gazebo.

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