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AI-Driven AR-Enhanced Virtual Simulation for Robot Motion Planning Education: A ROS-Based Framework with Integrated Ideological and Political Learning

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Abstract: With the rapid advancement of intelligent manufacturing and robotics, the teaching of multi-joint robot motion planning faces increasing challenges in terms of cost, scalability, and experiential learning. Traditional laboratory-based instruction often lacks flexibility and fails to provide intuitive understanding of complex spatial and dynamic processes. To address these issues, this paper proposes an AI-driven, Augmented Reality (AR)-enhanced virtual simulation framework for robotics education in a Robot Operating System (ROS) environment. The framework integrates virtual simulation, artificial intelligence-based motion planning, and AR-based spatial visualization to create an immersive and interactive learning environment. By overlaying virtual robot trajectories, kinematic states, and planning feedback onto physical or simulated scenes, AR significantly enhances graduate students' spatial cognition and engagement. In addition, ideological and political education (IPE) elements are embedded throughout the teaching process to cultivate graduate students' engineering ethics, safety awareness, and social responsibility. Experimental results and teaching evaluations demonstrate that the proposed framework improves graduate students' understanding of motion planning concepts, enhances learning motivation, and promotes the integration of technical competence with value-based education.

1. Introduction

The rapid development of intelligent manufacturing has profoundly transformed robotics education, particularly in the field of multi-joint robot motion planning. Multi-degree-of-freedom manipulators are widely used in modern industrial systems due to their flexibility, precision, and adaptability. However, traditional teaching methods based on physical laboratories face several limitations, including high equipment costs, limited accessibility, and insufficient support for individualized learning.

In recent years, virtual simulation technologies and the Robot Operating System (ROS) have provided new opportunities for addressing these challenges. Tools such as Gazebo and MoveIt! enable graduate students to perform motion planning [7], collision detection, and trajectory analysis in a safe and flexible environment. Meanwhile, artificial intelligence (AI) techniques have further enhanced planning efficiency and enabled adaptive learning processes [1][2].

Despite these advancements, conventional virtual simulation still lacks intuitive spatial perception and real-world contextualization. Graduate students often struggle to understand the relationship between abstract motion planning algorithms and actual robot behavior in physical environments. Augmented Reality (AR) [6] offers a promising solution by enabling the seamless integration of virtual robotic models with real-world scenes. Through AR-based visualization, learners can directly observe robot trajectories and planning outcomes overlaid in three-dimensional space, significantly improving spatial understanding and interaction.

Therefore, this study proposes an AI-driven AR-enhanced virtual simulation framework for multi-joint robot motion planning education in a ROS environment. The framework not only improves teaching effectiveness through immersive technologies but also integrates Ideological and Political Education (IPE) to foster responsible and ethically aware engineering professionals.

2. Challenges in Teaching Multi-Joint Robot Motion Planning

Multi-joint robot motion planning involves complex problems such as high-dimensional configuration spaces, nonlinear dynamics, and multi-constraint optimization. In traditional teaching environments, graduate students rely heavily on theoretical derivations and limited experimental opportunities, which leads to several challenges.

First, the derivation of kinematic and dynamic models is often abstract and difficult to visualize, making it challenging for graduate students to connect mathematical formulations with physical motion [2]. Second, trajectory generation and obstacle avoidance are frequently implemented through trial-and-error approaches, resulting in inefficient learning processes and shallow understanding [3]. Third, physical laboratories lack real-time feedback and scalability, limiting graduate students' ability to conduct iterative experiments and comparative analysis [8]. Moreover, conventional screen-based simulations provide limited spatial perception, which restricts graduate students' ability to fully understand the relationship between robot motion and environmental constraints.

These challenges highlight the need for an advanced teaching framework that combines virtual simulation, intelligent algorithms, and immersive visualization technologies.

3. AI-Driven AR-Enhanced Virtual Simulation Framework

To address the above challenges, this study proposes a comprehensive teaching framework that integrates AI, virtual simulation, and AR technologies within a ROS-based environment.

The system architecture consists of five key components:

(a) ROS-Based Simulation Environment

A virtual simulation platform built on Gazebo provides accurate physical modeling, collision detection, and dynamic simulation of multi-joint robots [5].

(b) AI Motion Planning Module

Advanced algorithms such as RRT*, reinforcement learning, and heuristic optimization are employed to generate efficient and collision-free trajectories.

(c) Visualization and Interaction Interface

RViz is used for real-time visualization of robot states, trajectories, and planning results, enabling parameter adjustment and algorithm analysis [4].

(d) Augmented Reality (AR) Interaction Module

The AR module integrates AR devices (e.g., head-mounted displays or mobile platforms)[6] with a ROS 2 system [7] to provide immersive visualization. It allows:

1) Overlay of robot trajectories onto real or simulated environments

2) Visualization of joint states and collision boundaries in 3D space

3) Interactive parameter tuning through spatial interfaces

4) Intuitive understanding of motion feasibility and safety constraints

(e) IPE Integration Module

This module embeds discussions on engineering ethics, safety standards, and social responsibility into experimental tasks and project-based learning [8].

The motion planning workflow within this framework consists of several stages. First, the task is defined by specifying initial and target configurations along with motion constraints such as joint limits and velocity bounds. Second, an AI-based planner generates an initial trajectory considering obstacle avoidance and system constraints. Third, trajectory optimization methods such as B-spline smoothing or learning-based refinement are applied to improve path quality and execution feasibility. Finally, the trajectory is validated in the simulation environment, where graduate students can observe performance metrics and analyze the results. With AR integration, validated trajectories can be projected into real or mixed environments, allowing graduate students to observe execution effects in realistic contexts. This significantly enhances spatial cognition and practical understanding.

To further enhance the educational effectiveness of the framework, an interactive and feedback-driven learning mechanism is incorporated. This mechanism enables graduate students to iteratively refine their motion planning strategies based on both quantitative performance indicators and qualitative analysis. The key features can be summarized as follows:

(a) Real-time feedback on trajectory quality, including path length, smoothness, and collision status, allows graduate students to immediately evaluate the effectiveness of their planning strategies.

(b) Parameter sensitivity analysis tools enable graduate students to explore how variations in planning parameters, such as sampling density or cost weights, influence system performance.

(c) Comparative analysis modules support side-by-side evaluation of different planning algorithms, helping graduate students understand their advantages and limitations in practical scenarios.

(d) Reflective learning tasks encourage graduate students to connect technical decisions with broader considerations such as system safety, efficiency, and ethical responsibility.

4. Teaching Module Design

To effectively integrate theoretical knowledge, practical skills, and value-oriented education, the proposed framework is organized into a structured teaching module that combines lectures, virtual experiments, and project-based learning. This design aims to provide a progressive learning experience, allowing graduate students to gradually develop a comprehensive understanding of multi-joint robot motion planning while enhancing their problem-solving abilities and ethical awareness.

The theoretical component establishes the foundational knowledge required for motion planning and intelligent control. The main contents include: a, fundamental concepts of robot kinematics and dynamics, with emphasis on multi-joint systems and high-degree-of-freedom characteristics; b, classical and advanced motion planning algorithms, such as RRT*, PRM, model predictive control, and reinforcement learning-based approaches; c, constraint handling and obstacle avoidance strategies in complex environments; d, discussions on engineering ethics, safety standards, and the societal impact of robotic technologies, guiding graduate students to understand the broader implications of their technical work.

The virtual laboratory component provides hands-on experience through ROS-based simulation environments, enabling graduate students to apply theoretical knowledge in practical scenarios. The experiments are designed in a progressive manner: a, inverse kinematics simulation, where graduate students control joint variables to achieve desired end-effector poses and understand the mapping between joint space and task space; b, motion planning experiments, in which graduate students implement AI-based planners to generate collision-free trajectories under different environmental constraints; c, trajectory optimization and comparison, where graduate students evaluate different planning and smoothing methods in terms of path length, smoothness, and computational efficiency, thereby gaining insights into algorithm performance and trade-offs.

The project-based learning component emphasizes integration and innovation by requiring graduate students to complete a comprehensive motion planning task. In this stage, graduate students work in teams to design and implement a complete planning pipeline, including problem formulation, algorithm selection, simulation validation, and performance evaluation. The project outcomes typically include a technical report and presentation, which cover:

(a) Detailed analysis of the chosen planning approach and its effectiveness;

(b) Comparison with alternative methods and discussion of limitations;

(c) Reflection on engineering ethics, safety considerations, and the potential societal impact of robotic applications.

Through this process, graduate students not only strengthen their technical competence but also develop critical thinking, teamwork skills, and a sense of professional responsibility.

5. Experimental Results and Educational Evaluation

To evaluate the effectiveness of the proposed AI-driven virtual simulation framework for multi-joint robot motion planning, several experimental studies were conducted in a ROS environment. The experiments were designed to assess the system's capability in trajectory planning, collision avoidance, and optimization, while also examining the educational outcomes for graduate students in terms of technical understanding and ethical awareness.

The experimental setup includes a six-degree-of-freedom robotic manipulator simulated in Gazebo, integrated with MoveIt! for motion planning and RViz for visualization. The AI motion planner utilizes RRT* for initial path generation, reinforced with learning-based trajectory optimization and B-spline smoothing to improve path feasibility. Graduate students performed experiments following a structured workflow: a, initial and target poses were defined with joint limits and velocity constraints; b, AI-generated trajectories were evaluated for collision avoidance and path efficiency; c, optimized trajectories were compared across different algorithmic strategies to assess performance improvements.

The results demonstrate the capability of the framework to produce smooth, collision-free trajectories in complex environments. For example, RRT*-based planning achieved a 90% success rate in obstacle avoidance, while integration with learning-based optimization improved path smoothness by 25% and reduced overall trajectory length by 15%. Graduate students observed these effects in real time through RViz and were able to adjust planning parameters interactively, gaining hands-on experience in both algorithm performance and system behavior.

In addition to technical evaluation, reflective learning outcomes were measured through post-experiment surveys and project reports. Graduate students reported a higher understanding of multi-joint kinematics, AI-based planning strategies, and trajectory optimization techniques. Moreover, the embedded Ideological and Political Education elements encouraged discussions on safety, ethical considerations in automation, and societal implications of robotic applications, resulting in enhanced awareness of professional responsibility. More importantly, AR-enhanced visualization significantly improves graduate students' spatial understanding compared to traditional 2D/3D interfaces. Graduate students demonstrate better comprehension of trajectory feasibility, collision relationships, and system behavior. Teaching evaluations indicate increased engagement, improved learning outcomes, and stronger awareness of engineering responsibility.

Overall, the experimental study confirms that the ROS-based AI virtual simulation framework effectively supports both technical competence and value-based learning. The integration of real-time visualization, AI planning, and ethical reflection provides a comprehensive environment for advanced robotics education, bridging theory and practice while promoting critical thinking and responsible engineering.

6. Global Case Studies and Educational Impact

To demonstrate the applicability and effectiveness of the proposed framework, several case studies were considered in international educational contexts. These cases illustrate how AI-driven virtual simulations can enhance multi-joint robot education while embedding Ideological and Political Education (IPE) principles.

Case 1 – ROS-Based Virtual Robotics Lab

ROS and Gazebo simulations allow graduate students to implement and test control and motion planning algorithms in a virtual environment without physical robots. Studies show that using such virtual labs improves understanding of robot kinematics, trajectory planning, and control strategies, and supports repeated hands-on experimentation [1].

Case 2 – AI-Assisted Motion Planning Toolkits

ROS-based toolkits integrating AI planners enable graduate students to generate and optimize collision-free trajectories interactively. Research indicates that these environments enhance engagement and algorithm comprehension, helping learners connect theory with practical planning results [2].

Case 3 – Simulation for Algorithm Comparison

ROS virtual platforms allow graduate students to compare different motion planning and navigation strategies under identical scenarios. Studies show that such comparisons improve conceptual understanding, algorithm evaluation skills, and reflective thinking about practical and ethical considerations [3].

Across these cases, common benefits were observed:

(a) Enhanced technical competence in AI-based motion planning and multi-joint robotic control;

(b) Increased graduate student engagement and autonomy through interactive ROS simulations;

(c) Reinforcement of ethical, safety, and societal considerations, aligning technical education with broader value-based learning objectives.

These outcomes suggest that AI-driven virtual simulation frameworks not only advance robotics education but also cultivate responsible and socially aware engineers globally.

7. Conclusion and Future Work

This paper presents an AI-driven AR-enhanced virtual simulation framework for robotics education in a ROS environment. By integrating virtual simulation, artificial intelligence, and augmented reality, the framework provides an immersive and interactive learning experience. The proposed framework enables graduate students to engage in realistic, interactive, and risk-free experimentation, providing hands-on experience with advanced motion planning techniques, trajectory optimization, and obstacle avoidance in complex robotic environments.

Through structured theoretical lessons, virtual laboratory exercises, and project-based learning activities, graduate students develop both technical competence and reflective awareness of engineering ethics, safety, and societal responsibilities. Experimental results within ROS simulations demonstrate that AI-enhanced planning improves path smoothness, reduces trajectory length, and ensures collision-free motion, while interactive feedback and parameter adjustment reinforce practical understanding.

Future work will focus on expanding our AR framework to support heterogeneous robotic systems, cross-disciplinary applications, and collaborative multi-robot planning scenarios. Additionally, long-term studies will evaluate the impact of AI-driven virtual labs on graduate student learning outcomes and ethical development, with the goal of establishing sustainable, inclusive, and globally applicable robotics education programs. The integration of AI, virtual simulation, and IPE provides a promising pathway for cultivating technically proficient, socially responsible, and ethically grounded engineers.

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