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Exploration of Hybrid Reality Teaching Model for Robotics Technology Courses in Intelligent Manufacturing Era

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Abstract: The rapid development of intelligent manufacturing prompts universities to actively explore a new model of practical teaching of robot technology. The quality and efficiency of the training of innovative talents are restricted by the delayed updating of the teaching content of robot technology in colleges and universities, the serious shortage of practical resources and the lack of application background. Through school-enterprise cooperation and the combination of teaching and scientific research, it has established a comprehensive practical teaching resource of robot technology that integrates virtual simulation learning and training of software, virtual and real simulation training of software and hardware, and practical operation of hardware experiment, which simultaneously meets the needs of the whole teaching cycle such as theoretical teaching, functional verification and hardware practical operation. Through the practice of robot technology related courses in our school, it is shown that this model improves the teaching effect and students' professional level and skills of robot technology.

1. Introduction

Industrial robots, as a crucial foundation for implementing smart manufacturing, have witnessed an explosive growth in industrial application demands[1]. With the rapid development of the industrial robotics sector, enterprises are increasingly demanding professionals in smart manufacturing fields[2-3]. Therefore, exploring talent cultivation models in robotics technology, promoting the alignment of educational content with technological advancements and teaching processes with industrial production, and enhancing the efficiency and quality of cultivating high-level interdisciplinary professionals such as robotics engineers for intelligent manufacturing have become urgent issues to address in robotics technology education within higher education institutions[4-5].

In response to economic development demands, many universities' mechanical engineering programs have established over 10 core courses in smart manufacturing, including "Industrial Robotics", "Smart Manufacturing Technology", "Fundamentals of Testing Technology", and "Fundamentals of Artificial Intelligence"[6-7]. These robotics-related courses span multiple interdisciplinary fields such as mechanical design, control science, computer programming, and electronic technology, demonstrating strong theoretical depth and practical requirements. This inherent complexity not only increases the learning difficulty for students but also poses significant teaching challenges for educators. Currently, many institutions rely solely on multimedia tools or simulation software[8-9] for robotics instruction, resulting in low motivation and interest among students in learning robotics technology, and the students trained are noticeably deficient in practical operation skills, problem analysis capabilities, and error identification and correction. Furthermore, while some universities have implemented practical training modules, the prohibitive costs of industrial robots and safety concerns have led to severe shortages of experimental equipment. Consequently, students primarily acquire theoretical knowledge through classroom lectures, developing only superficial understanding of robotic operational principles. This lack of hands-on training creates deficiencies in practical competencies, coupled with insufficient integration between practical training content and industrial development.

The accelerated iterative evolution of artificial intelligence[10-11] has driven universities to actively explore innovative approaches for robotics technology practical education. Current robotics curricula in higher education exhibit delayed updates that fail to meet industrial demands, while severe shortages of practical resources and lack of application context constrain the quality and efficiency of innovative talent cultivation. This study proposes a virtual-physical integrated pedagogical framework for robotics practice, aiming to enhance instructional effectiveness and elevate students' professional competencies in robotics technology.

2. Comprehensive Practical Teaching System Design

Aiming to cultivate innovative capabilities aligned with the talent demands of robotics industrial development, this study proposes a cyber-physical integrated practical teaching framework for robotics education, illustrated in Figure 1. Departing from conventional purely physical or virtual training paradigms, this framework[12-15] strategically balances safety, cost efficiency, and pedagogical engagement through a virtual-reinforced-physical progressive methodology that transitions from virtual instruction to physical implementation, thereby systematically enhancing students' technical expertise in robotics. The model integrates three core components: hands-on hardware experimentation, software-based virtual simulation training, and hardware-software hybrid simulation. These components holistically address pedagogical requirements across the full instructional cycle, encompassing theoretical learning, virtual functional validation, and physical operational practice. This integrated approach not only serves as an effective platform for nurturing interdisciplinary robotics professionals such as R&D engineers but also substantially reduces reliance on specialized infrastructure and funding.

To effectively enhance students' comprehension of robotic internal architectures, the methodology first involves simulated disassembly, analysis, and "redesign" of mainstream robotic products; followed by virtual-physical integrated cognitive reinforcement of physical robotic components to deepen understanding of operational mechanisms.

To solve the problem of students lacking robotics engineering practical experience and feeling overwhelmed during training, virtual robot platforms are applied to programming design, using graphical modular programming to reduce coding difficulty; while students complete typical operations such as material handling, assembly, and spraying in virtual environments, physical robots synchronously replicate these actions, achieving virtual-physical collaboration. Through virtual-physical integrated dynamic tracking, real-time intuitive visualization of physical robots' motion performance is implemented, forming verification with theoretical analysis results.

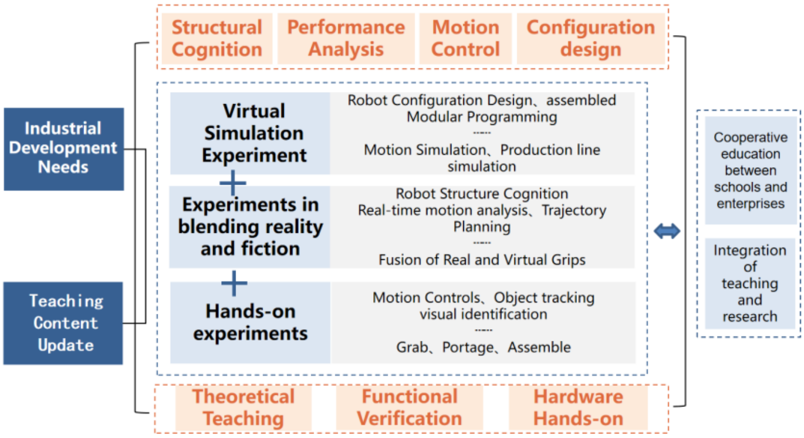


Figure 1: Virtual-Physical Integrated Practice Teaching Model for Robotics Technology Courses.

In digitally replicated work environments, path teaching is achieved by dragging robotic arm models with fingers or mouse, reducing costs and improving efficiency while advancing the practical implementation of robotics education and significantly enhancing experimental efficiency. The generated optimal paths are transmitted to physical robotic arms to drive their movements.

3. Strategic Planning for Comprehensive Practical Resource Development

3.1. Industry-Academia Symbiotic Talent Cultivation Mechanism

University-industry collaboration and industry-education integration serve as vital pathways to actively promote comprehensive structural alignment between the talent supply side of education and industrial demand side, achieving complementary advantages of talent, intellectual resources, and technological capabilities across educational and industrial systems[16-17].

To construct virtual-physical integrated practical teaching resources for innovative talent cultivation, the team conducted extensive market research and systematic planning addressing comprehensive robotics practice teaching models and instructional plans. Through investigations and analyses of enterprises including Beijing Xiangxinli, Zhejiang University Xuri, Tianjin Zhikong, Beijing Runier, as well as institutions like Zhejiang University Ningbo Institute of Technology, Hangzhou Dianzi University, and Chongqing University, a joint development agreement was ultimately established with Runier Corporation. During the comprehensive practical resource development process, Runier Corporation will provide technical support including mainstream robotic model libraries, typical case repositories, and virtual simulation platforms; based on the established practical teaching models and instructional plans, universities and enterprises collaboratively develop comprehensive design-oriented experiments that incorporate principles, methodologies, and technologies from multiple courses in intelligent manufacturing, as well as research-exploratory experiments introducing cutting-edge issues in robotics industry or technological advancements[18].

3.2. Symbiotic Integration of Pedagogical Practice and Academic Research

Traditional teaching methods remain confined to textbook knowledge transmission, where the updating pace of curricular content fails to match technological advancements, a limitation particularly pronounced in robotics technology education. Strengthening the mutual enhancement between teaching and scientific research holds significant importance for improving the effectiveness of higher education talent cultivation and fostering innovative professionals[19-20]. On one hand, instructors' integration of cutting-edge research findings into classroom instruction not only enriches teaching content but also stimulates student interest and enhances pedagogical outcomes. Meanwhile, the teaching process serves to distill complex research concepts into accessible knowledge, during which educators may identify previously unnoticed research questions or directions, thereby gaining novel insights that reciprocally inform scientific investigation.

At Ningbo University's School of Mechanical Engineering, both undergraduate and postgraduate programs offer courses including Smart Manufacturing Technology and Industrial Robotics, alongside robotics-focused adult education programs, supported by dedicated faculty teams and specialized laboratories. To cultivate smart manufacturing talents meeting the demands of coastal manufacturing enterprises, the school actively explores innovative talent cultivation models for entrepreneurship education under new circumstances, leveraging its software and hardware resources. The development of virtual-physical integrated practical resources for robotics technology in this study is anchored in the university's robotics research group and Virtual Simulation Teaching Laboratory, forming a development team comprising 6 core faculty members and 2 newly recruited postgraduate students annually, while also engaging undergraduate teams through training programs. This research-teaching integrated approach provides intelligent practical teaching systems for core course instruction and laboratory sessions. Addressing the interdisciplinary nature and highly practical requirements of robotics courses, along with constraints like high costs and safety concerns, the development team conducts virtual-physical integrated teaching resource planning for typical teaching modules, focusing on knowledge points that students find conceptually challenging and operationally demanding.

Students participating in scientific research activities not only gain enhanced opportunities for exploration and innovation that improve their professional skills and innovative thinking, but also cultivate proper academic ethics and a spirit of national ethos and social responsibility[19], demonstrating significant enhancement in holistic competencies.

4. Pedagogical Implementation Cases

Through in-depth discussions and iterative evaluations between the university and enterprise partners regarding the development planning, instructional design, and collaboration models for robotics practical resources, eight representative case studies have been developed. These include virtual simulation experiments on robotic configuration and programming training, virtual-physical interactive quadruped robot locomotion simulations, robotic arm trajectory planning experiments, human-machine interaction and anthropomorphic patrol experiments with robotic canines, as well as vision-guided robotic arm harvesting and grasping/clamping experiments[21-22]. These cases virtually reconstruct practical processes challenging to implement in physical teaching environments, translating abstract theoretical knowledge into operational practice. The following case serves as an illustrative example.

4.1. Hybrid Reality Locomotion Simulation for Quadruped Robotic Dog

The physical implementation features an AI vision-enabled quadruped robotic dog developed based on Raspberry Pi, shown in Figure 2, which utilizes the ROS operating system to achieve basic gaits including free locomotion and stair climbing/descending. The software system, built upon

Android technology, operates on mobile devices or other Android OS-equipped platforms, employing multi-terminal real-time communication technology to synchronize motion states between simulation software and the physical quadruped robot, as demonstrated in Figures 3 and 4.

Augmented reality (AR) visualization methods superimpose kinematic analysis parameters – such as the robot's center of gravity, joint angles, and safe operational workspace – onto live camera feeds. This virtual-physical integration enables comprehensive real-time analysis of robotic motion, integrating stability monitoring and operational safety assessments within a unified framework.

Figure 2: Quadruped Robot.

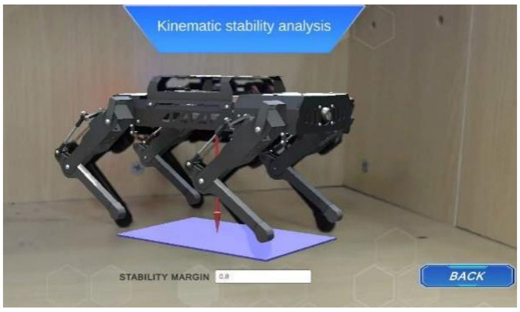


Figure 3: Real-Time Analysis of Gait and Center of Mass (CoM) Trajectory.

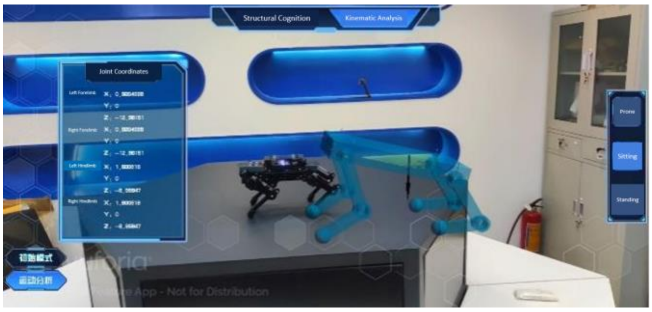
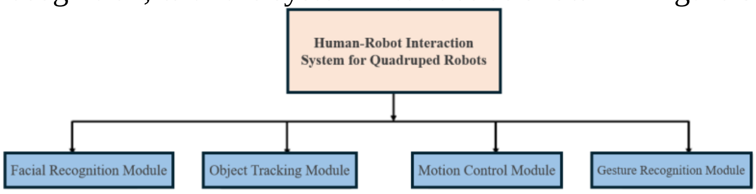


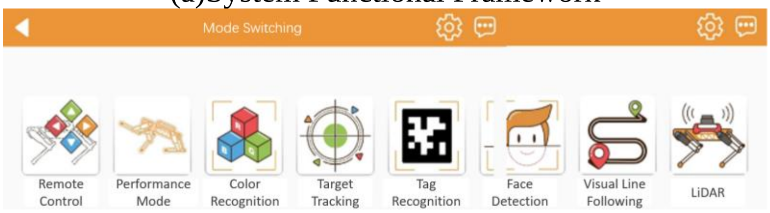
Figure 4: Real-Time Kinematic Analysis for Quadruped Robot.

4.2. HRI Experiments with Quadruped Robotic Dog

The interactive experiment comprises four modules: face recognition, object tracking, motion control, and gesture recognition, with the system interface as shown in Figure 5.



(a)System Functional Framework



(b)Real-Time Kinematic Analysis of Quadruped Robot

Figure 5: Real-Time Kinematic Analysis of Quadruped Robot.

The facial recognition module performs real-time detection of student expressions and reactions, triggering responsive actions through instant feedback mechanisms to effectively enhance engagement and learning motivation; The object tracking module equips the robotic dog with agile mobility and interactive capabilities, enabling active approaching, following, or obstacle avoidance operations to deliver intelligent service experiences across diverse scenarios; The motion control module processes user commands via real-time analytical algorithms to precisely coordinate Quadruped Robot components, executing maneuvers including forward/backward movement, directional turns, sitting/standing postures, thereby enhancing interactive experiences with heightened flexibility and intelligent responsiveness; The gesture recognition module interprets specific manual commands to initiate corresponding actions such as sitting, standing, and pivoting, facilitating intuitive human-canine interaction while enabling students to comprehend the robotic dog's behavioral mechanisms, deepen understanding of kinematic principles through observable command-to-action conversion processes, and systematically master technical fundamentals and application methodologies.

4.3. Modular Configuration and Programming Experiments for Robotic Arm

The enterprise provides assembly processes for ten representative categories of robots, enabling users to select components from the parts library and drag-drop them into the main workspace for robotic configuration and structural assembly.

The programming experiment utilizes a multi-functional intelligent robotic arm with first-person vision, shown in Figure 6, which employs the ROS operating system and supports graphical programming. The Blockly-based visual programming interface for the smart vision robotic arm enables code logic construction through dragging modules. Exemplary multi-joint angle configurations established through Blockly-based graphical programming are demonstrated in Figure 7.

Figure 6: Robotic Manipulator.

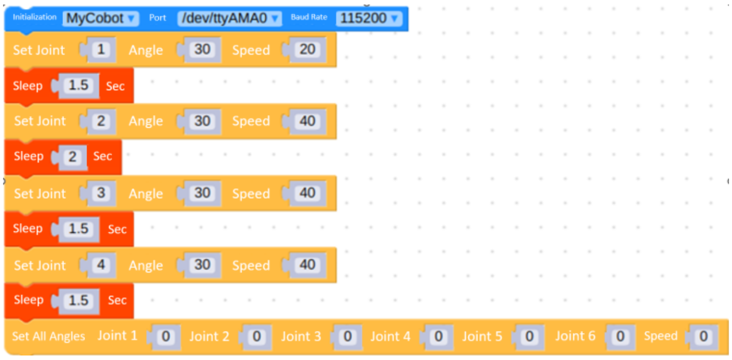
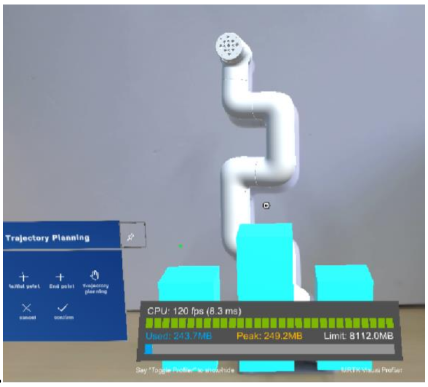


Figure 7: Multi-Joint Angle Configuration Demonstration for Robotic Arm.

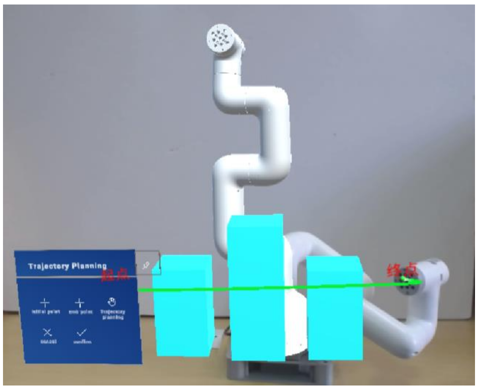
This training enables students to comprehend the fundamental principles and structural configurations of six-axis robotic arms, perform angular calculations and kinematic pattern analyses; master programming methodologies for six-axis manipulators, developing and debugging control programs for arm motions; familiarize with industrial application scenarios of six-axis robots, designing and implementing grasping/clamping operations according to practical requirements; while students complete virtual implementations of typical industrial tasks such as material handling, assembly, and spraying in digital environments, physical counterparts synchronously replicate these operations through virtual-physical synchronization.

4.4. Trajectory Planning Experiments for Robotic Arm in Digital Engineering Scenarios

Motion trajectory planning serves as the core mechanism for achieving efficient and precise movements in industrial robotic arm. Although teaching-based trajectory planning methods provide intuitive visualization and rapid deployment, they are inherently associated with elevated safety hazards and substantial operational costs. To overcome these challenges, our methodology employs digital twin technology to replicate the robotic workspace through precise 1:1 three-dimensional modeling of both the robotic arm and environmental obstacles. By interactively manipulating the virtual arm model via touch or mouse inputs, collision-free motion trajectories are autonomously generated using integrated collision detection algorithms and trajectory optimization modules, as depicted in Figure 8(a) and Figure 8(b). This virtual simulation environment facilitates real-time visualization and refinement of motion paths, effectively mitigating mechanical wear, accelerating programming workflows, and improving operational efficiency. The finalized optimized trajectories are then transmitted to physical robotic systems for execution, demonstrated in Figure 8(c) and Figure 8(d).



(a) Robotic Manipulator Model Registration



(b) Trajectory Planning

(c) Physical Environment of Robotic Manipulator

(d) Physical Motion Execution of Robotic Manipulator

Figure 8: Optimization-Based Motion Trajectory Planning for 6-DOF Serial Manipulator.

5. Conclusion

Augmented Reality (AR) technology's extensive applications have introduced novel approaches and tools for practical robotics education. The virtual-physical integrated pedagogical resources encompassing "hands-on hardware experimentation", "software virtual simulation training", and "hardware-software integrated practice" simultaneously address educational requirements across the complete pedagogical cycle, including theoretical instruction, virtual functional verification, and physical operational validation. This dual-emphasis teaching paradigm strategically balances safety, cost-effectiveness, and learner engagement while mitigating resource scarcity, thereby enhancing the efficiency and quality of cultivating advanced interdisciplinary professionals like smart manufacturing-oriented robotics engineers. The industry-academia collaborative development model, integrating educational and research activities, achieves seamless alignment between curricular content, industrial demands, and technological advancements, significantly improving the convergence between talent cultivation and industrial technical evolution.

This research provides substantial support for effectively enhancing the quality of talent cultivation in this discipline at our institution, while also offering valuable references and empirical insights for practical teaching reform in robotics technology within the smart manufacturing paradigm.

Acknowledgements

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