

Innovative Practical Teaching in Robotics Based on Digital Twin

Bin Gao ¹, Xiaopeng Li ², Zhihui Miao ² and Ying Wang ^{1,*}

¹ School of Robotics and Advanced Manufacture, Harbin Institute of Technology, Harbin, 518055, China

² Experimental and Creative Practice Education Center, Harbin Institute of Technology, Shenzhen, 518055, China

* Correspondence: Ying Wang, School of Robotics and Advanced Manufacture, Harbin Institute of Technology, Harbin, 518055, China

Abstract: The rapid advancement of digital technologies has established digital twin platforms as crucial tools for industrial modernization. Integrating this technology into robotic practice teaching facilitates the construction of an intelligent educational paradigm that bridges virtual and physical realms. This integration overcomes traditional teaching limitations, including constrained physical resources, operational risks, and confinement to single-use scenarios. The Rabo robot digital twin system combines a robotic dynamics simulation engine with an intelligent control system, enabling real-time data interaction and synchronized control with physical entities. Its key functionalities include virtual simulation and remote operation. Through practical teaching applications, this system enhances the efficiency of robot algorithm verification and motion control, thereby significantly supporting robotic experimental education and technical validation. Furthermore, it plays a pivotal role in cultivating students' innovative practical skills.

Keywords: practical teaching; digital twin; robotics; Rabo

1. Introduction

Digital Twin technology involves creating a digital representation of a physical entity within a virtual space. By leveraging physical models, sensor data, and other information it facilitates multidisciplinary, multi-physical, and multi-scale simulations, offering novel insights for robotic practice teaching ^[1-3].

Accordingly, we designed and developed a robotic experimentation platform based on digital twin technology. This platform integrates virtual simulation, real-time communication, and 3D visualization to achieve real-time monitoring, remote control, and virtual-physical synchronization for sorting robotic arms. Using this platform, students can simulate and control robots via a computer interface without relying on traditional teach pendants. This approach effectively lowers the learning barrier while enhancing comprehension and practical skills in robot design and control, providing an efficient and innovative solution for robotics practice education ^[4-6].

Beyond its direct application in robotic teaching, the integration of digital twin technology into educational platforms reflects a broader trend in engineering pedagogy, where immersive, interactive, and data-driven tools are increasingly emphasized. The capability to merge theoretical knowledge with hands-on experimentation in a seamless manner allows students to bridge the gap between abstract learning and real-world problem-solving. Furthermore, as robotics continues to evolve with artificial intelligence, machine vision, and human-robot interaction, embedding digital twin frameworks into teaching practices prepares learners for complex interdisciplinary challenges. This alignment with emerging industrial demands highlights the dual role of digital twins, not only

Published: 12 October 2025



Copyright: © 2025 by the authors. Submitted for possible open access publication under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

as a technological advancement but also as a pedagogical innovation that fosters adaptability, creativity, and critical thinking among students.

2. Rabo Digital Twin Robot Platform

As shown in Figure 1, the Rabo system is a Browser-Server (B/S) architecture digital twin platform comprising a robot dynamics simulation engine and an intelligent control system. It provides a rapid prototyping environment where users can construct 3D virtual worlds with defined physical properties (e.g., mass, joints, friction coefficients). Users can incorporate passive objects or active entities termed "robots." These robots can adopt various locomotion schemes (e.g., wheeled, legged, or aerial) and be equipped with sensors and actuators such as LiDAR, cameras, force/torque sensors, IMUs, and motors. Users can then program control logic for each robot. Beyond virtual simulation, Rabo executes user-written control programs on physical hardware via its intelligent control system.

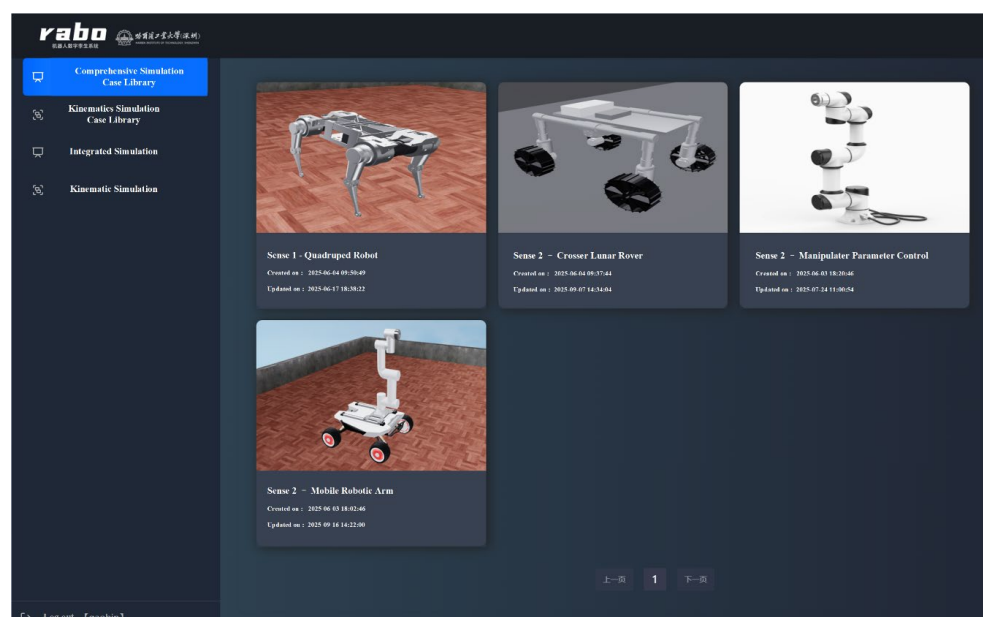


Figure 1. Rabo Digital Twin Robot Platform.

During development, cloud technology was integrated to consolidate hardware and software resources on servers. Instructors distribute login accounts, allowing students to access the Rabo platform via a web browser on a campus LAN to create simulation models and write control programs without requiring local software installation or environment configuration.

The hardware system consists of a cloud server, an on-site server, a central router, edge control computers (industrial PCs), power supplies, motors, motor controllers, and sensors. The cloud server is primarily responsible for data computation for the web-based simulation system. The on-site server collects and stores local data and communicates with the cloud server. The central router establishes the local network environment, ensuring all controllers and motors reside on the same LAN, enabling control of motors and sensors upon receiving commands from the web interface. The edge control computer is an industrial PC running a ROS2 environment, responsible for communicating with and controlling the actuators and sensors.

The combination of these components not only ensures efficient simulation-to-reality synchronization but also establishes a scalable infrastructure capable of supporting increasingly complex robotic experiments. By integrating cloud computing with edge control, the platform achieves both high computational efficiency and low-latency interaction, making it suitable for real-time educational scenarios. Moreover, the modular design of

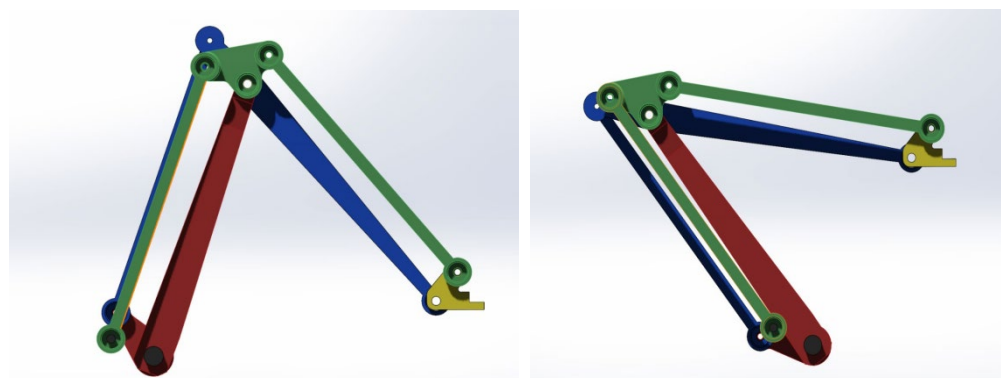
the Rabo system allows future extensions, such as incorporating advanced perception algorithms, multi-robot coordination mechanisms, or AI-driven adaptive control. From an educational perspective, this design philosophy provides students with exposure to a realistic, industry-aligned environment, preparing them to engage with modern robotic systems that rely on distributed computing, networked control, and cyber-physical integration.

3. Robot Structural Design

To facilitate the design and practical use of robotic arms, the platform provides three joint motors, enabling the design and digital twin control of a three-degree-of-freedom robotic arm. Two joint motor types are provided: the PP11L-36_V3, weighing 517g with a rated power of 72W and a maximum output torque of 12Nm, and the PP08-36_V3, weighing 190g with a rated power of 36W and a torque of 1Nm. The former offers robust driving power and stability, while the latter minimizes additional system inertia while meeting torque requirements.

The robot mechanism employs a parallel four-bar linkage. Driving the robot with two active links enables arbitrary positioning of the end-effector within the workspace while maintaining a constant end-effector orientation.

As shown in Figure 2, the two active links are marked in red. According to the parallelogram principle, the green link on the left is parallel to the red active long link. Because the lower hinges of both the left green link and the red active long link are fixed, the orientation of this parallelogram remains constant. Furthermore, as the upper green triangle is a rigid body with a fixed left-side orientation, the orientation of its right side is also fixed. Consequently, the orientation of the right parallelogram's sides is fixed, ensuring the yellow end-effector maintains a constant posture. By actuating the two red links, the robot performs arbitrary planar positioning operations within the workspace without altering the end-effector's orientation. This design is highly beneficial for drawing and table tennis picking operations, as it eliminates the need to actively manage the end-effector posture; a pen can be fixed vertically to the end-effector, and similarly for a gripper.



(a) Robot arm in the lowered position

(b) Robot arm in the raised position.

Figure 2. Parallel quadrilateral mechanical arm model.

From an engineering perspective, the use of a parallel four-bar linkage not only simplifies the control logic but also reduces the computational burden typically associated with inverse kinematics. This makes the system more efficient and accessible for students who may be encountering robotic mechanisms for the first time. Furthermore, the constant orientation of the end-effector is particularly advantageous for educational scenarios, where learners can focus on trajectory planning, control algorithms, and system integration without being constrained by complex orientation management. In future implemen-

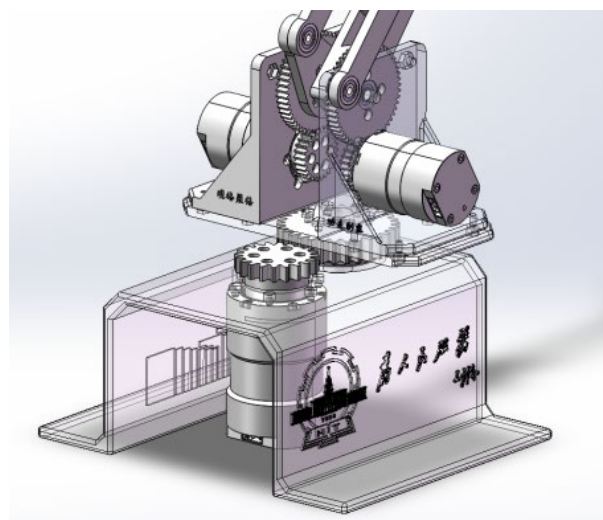
tations, additional degrees of freedom could be introduced to extend the platform's applicability to more sophisticated tasks, such as assembly, object manipulation, or multi-robot cooperation. Such expansions would further enhance the platform's value as both a teaching tool and a testbed for advanced robotic research.

We also incorporated a rotatable single-degree-of-freedom base, motor mounting plates, and gear reduction mechanisms. Two gear reductions were designed: a larger reduction for the base joint and a smaller one for the arm linkages. The larger mechanism uses a 1mm module gear for a 1.5:1 reduction ratio, while the smaller mechanism uses a 0.5mm module gear for a 2:1 reduction ratio. Bearing supports enhance the smoothness and precision of the arm's movement. The implementation of these gear reduction mechanisms and bearing supports not only improves the mechanical efficiency of the robotic arm but also provides more precise control over the motion of both the base and the arm links. This allows students to observe and analyze the direct relationship between gear ratios, torque output, and movement accuracy in a tangible way. From an educational standpoint, such a setup demonstrates fundamental mechanical principles, including leverage, rotational dynamics, and load distribution, within a real-world context. Furthermore, the modularity of the base and gear design allows for future modifications and experimentation, such as testing different reduction ratios, integrating alternative actuators, or exploring more complex robotic configurations, thus enriching the platform's versatility for teaching and research purposes.

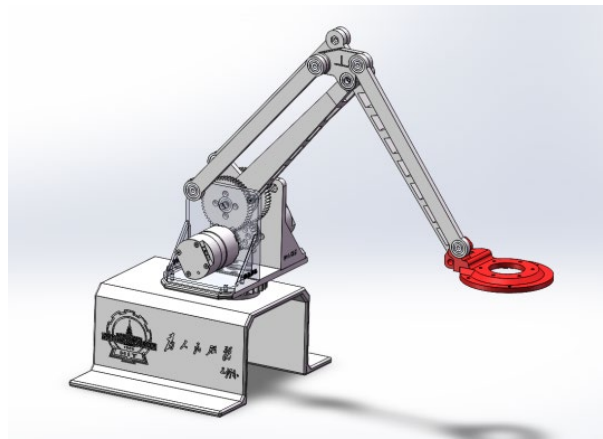
Using the Tuozhu Lab X1 3D printer, the robot prototype was fabricated from inexpensive, lightweight, yet sufficiently strong PLA material. This approach significantly shortens the manufacturing cycle from conceptual design to physical prototype while ensuring the dimensional accuracy and surface quality of components with complex geometries.

Through precise 3D modeling and optimized printing parameters (e.g., layer height, printing speed, infill density, support structures), the dimensional fits of key functional parts, such as shaft-hole interfaces, meet usage requirements.

As Figure 3 shows, the movement of each joint in the assembled manipulator prototype is smooth and fluid, without significant sticking or abnormal noise. The end-effector's posture maintenance function is stable and reliable throughout the entire workspace. The gear transmission system operates smoothly with adequate accuracy, and the bearing fits are precise, exhibiting low and uniform rotational resistance.



(a) Robot base mechanical structure.



(b) Parallel Four-Bar Robot Arm Design.



(c) Completed 3D printed mechanical arm.

Figure 3. Overall structure of the robotic arm.

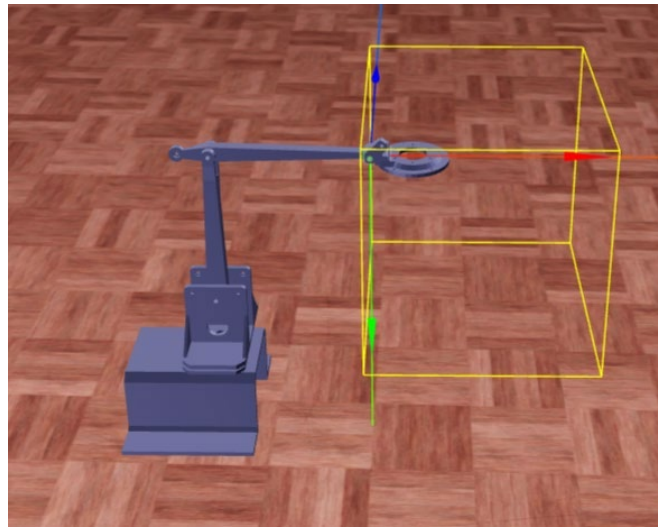
The use of 3D printing for prototyping not only accelerates the design iteration process but also provides an accessible platform for students to explore mechanical fabrication techniques firsthand. By directly engaging with material selection, print orientation, and parameter optimization, learners can observe how design decisions impact the functional performance of the manipulator. Moreover, the combination of rapid prototyping with digital twin simulations allows for a full-cycle educational experience, where theoretical design, virtual testing, and physical validation are seamlessly integrated. This approach enhances students' understanding of the interplay between CAD modeling, manufacturing constraints, and mechanical performance, thereby bridging the gap between classroom learning and real-world engineering applications.

4. Rabo Robot Simulation Scene Construction

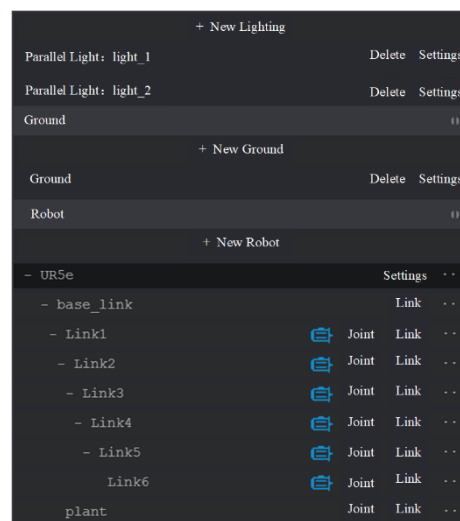
In the Rabo system, robots are composed of "parts" and "joints." Parts define visual models, collision models, and physical properties for each entity, while joints specify connection types (e.g., revolute, prismatic), axes of rotation, limits, and dynamics. Rabo supports the URDF format for importing robot models, enabling efficient configuration.

As the manipulator contains several parallel four-bar linkages, which are challenging to model directly in the simulation platform, an equivalent simplification was necessary. This configuration was equivalent to a 3R elbow manipulator, with a fourth joint introduced to maintain the end-effector's horizontal orientation. As shown in Figure 4, the exported URDF model was imported into the simulation platform. The position and axis

direction of each joint were verified for correctness. Position motors were added to each joint for control, alongside motor position sensors.



(a) Importing URDF robot model into simulation environment



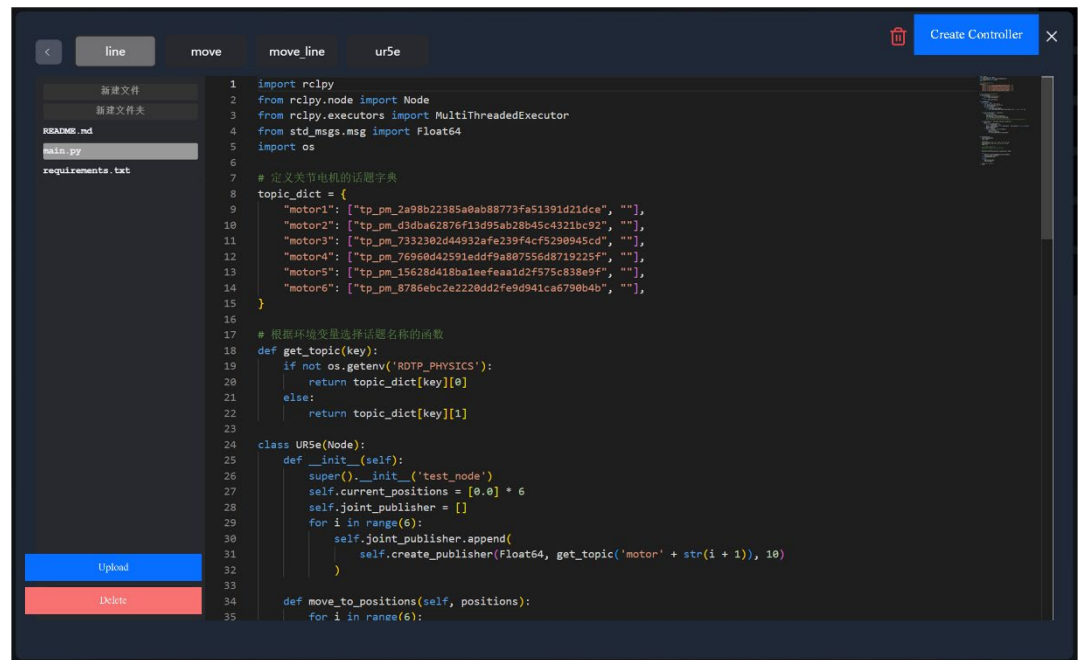
(b) Set up joint drive motor and position sensor.

Figure 4. Rabo Digital Twin Robot Platform.

By adopting this equivalent simplification, the platform reduces the complexity of simulation without compromising the accuracy of motion representation. This approach not only accelerates model verification and control development but also allows students to understand the principles of kinematic simplification and the trade-offs between modeling precision and computational efficiency. Additionally, importing URDF models streamlines the integration of theoretical designs into the simulation environment, reinforcing the connection between CAD-based modeling, virtual testing, and physical prototyping. From an educational perspective, this process exposes learners to industry-standard modeling practices, promoting a deeper comprehension of robotic configuration, joint dynamics, and the practical challenges of simulating multi-link mechanisms.

5. Rabo Digital Twin Practice

In practice, the system generates default files including main.py (the core entry point), a readme file, and requirements.txt, as shown in the figure 5. Program logic can be extended by modularizing code into multiple files to manage complexity. The platform enables motor control and sensor data processing, utilizing callback functions to listen to sensor data.



```

1 import rclpy
2 from rclpy.node import Node
3 from rclpy.executors import MultiThreadedExecutor
4 from std_msgs.msg import Float64
5 import os
6
7 # 定义关节电机的话题字典
8 topic_dict = {
9     "motor1": ["tp_pm_2a98b22385a8ab88773fa51391d21dce", ""],
10    "motor2": ["tp_pm_d3dba62876f13d95ab28b45c4321bc92", ""],
11    "motor3": ["tp_pm_7332302d44932afe239f4cf5298945cd", ""],
12    "motor4": ["tp_pm_76960d42591eddf9a807556d8719225f", ""],
13    "motor5": ["tp_pm_15628d418ba1eeffaad2f575c838e9f", ""],
14    "motor6": ["tp_pm_8786ebc2e2228dd2fe9d941ca6790b4b", ""],
15 }
16
17 # 根据环境变量选择话题名称的函数
18 def get_topic(key):
19     if not os.getenv('RDTP_PHYSICS'):
20         return topic_dict[key][0]
21     else:
22         return topic_dict[key][1]
23
24 class UR5e(Node):
25     def __init__(self):
26         super().__init__('test_node')
27         self.current_positions = [0.0] * 6
28         self.joint_publisher = []
29         for i in range(6):
30             self.joint_publisher.append(
31                 self.create_publisher(Float64, get_topic('motor' + str(i + 1)), 10)
32             )
33
34     def move_to_positions(self, positions):
35         for i in range(6):

```

Figure 5. Rabo Digital Twin Robot Platform Controller.

As shown in Figure 6 and Figure 7, using the drawing of an arc trajectory as an example, the manipulator's end-effector in the simulation can rapidly move to a specified point within the workspace. It can trace a straight line between defined start and end points and move horizontally along a circle of a specified center and radius.

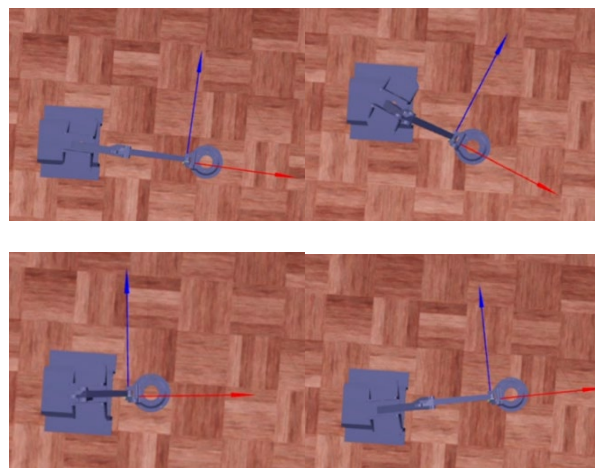


Figure 6. Robot draws an arc in the Rabo Digital Twin Robot Platform.

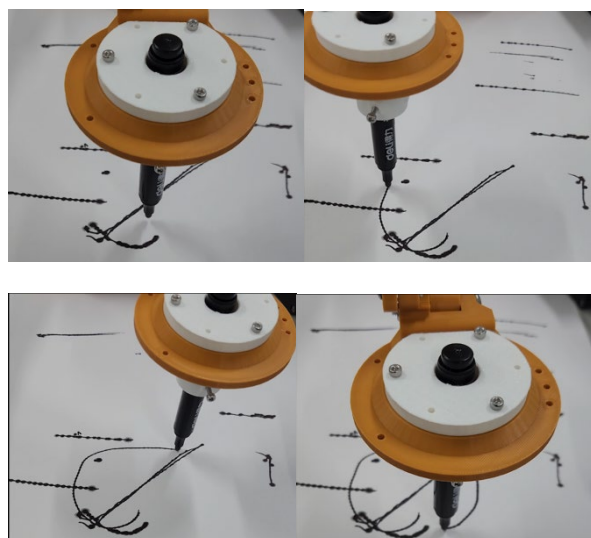


Figure 7. Remote-controlled robot draws an arc.

During physical operation, the manipulator's end-effector successfully performed these tasks. However, the position control was initially slow, with noticeable stuttering at path segmentation points. After further debugging and adjusting temporal parameters, the system executed trajectories such as circles more smoothly.

This modular and structured approach to program design not only simplifies the development and debugging process but also provides students with a clear framework for learning software engineering principles in robotics. By separating core functions, sensor handling, and motor control into distinct modules, learners can focus on individual components without being overwhelmed by overall system complexity. Moreover, the ability to simulate precise trajectories, such as arcs and lines, offers hands-on experience in trajectory planning, motion control, and real-time feedback processing. Such capabilities enhance understanding of the interplay between software logic, robotic kinematics, and sensor integration, thereby bridging theoretical concepts with practical implementation. This design also lays the foundation for future extensions, including more complex trajectory algorithms, multi-robot coordination, and adaptive control strategies, further enriching the educational and research potential of the platform.

6. Conclusion

The development of the Rabo digital twin robot practice platform introduces a novel approach to robotics education, delivering functionalities such as virtual simulation, real-time control, and status monitoring. Through its virtual-real synchronization technology, the platform lowers the threshold for experimental operations, enhances system interactivity and real-time performance, and improves the intuitiveness of the teaching process. The Rabo platform demonstrates high virtual-real consistency and operational stability, accurately reflecting the physical system's motion state. It serves as a valuable new tool for experimental teaching with sorting robots, aiding in the development of students' engineering practical abilities and systems understanding, thereby possessing significant teaching application value. In addition, the Rabo platform exemplifies the integration of emerging digital technologies with traditional engineering education, fostering a learning environment that encourages experimentation, problem-solving, and critical thinking. By providing immediate feedback on virtual and physical operations, students can iteratively refine control strategies and design choices, reinforcing theoretical knowledge through hands-on experience. Furthermore, the platform's modular architecture and compatibility with various robotic configurations allow for scalable educational scenarios, from basic manipulator training to complex multi-robot coordination tasks. This adaptability not

only enhances the platform's pedagogical value but also prepares students for industry-standard practices in robotics, automation, and cyber-physical systems, bridging the gap between academic learning and professional application.

References

1. L. Guangyu, P. A. N. G. Xinyu, L. I. Shuojie, S. H. I. Bozhao, and L. I. U. Dengyu, "Application of a digital twin in virtual simulation experiment teaching of the control course," *Experimental Technology & Management*, vol. 41, no. 3, 2024.
2. W. Tarng, Y. J. Wu, L. Y. Ye, C. W. Tang, Y. C. Lu, T. L. Wang, and C. L. Li, "Application of virtual reality in developing the digital twin for an integrated robot learning system," *Electronics*, vol. 13, no. 14, p. 2848, 2024.
3. E. A. Avila, D. P. Chapa, I. D. Arenas, and C. V. Hurtado, "A Digital Twin implementation for Mobile and collaborative robot scenarios for teaching robotics based on Robot Operating System," In *2022 IEEE Global Engineering Education Conference (EDUCON)*, March, 2022, pp. 559-564.
4. Q. Zhou, H. Jiang, and Z. Lei, "Research on the Application of Twin Technology in the Teaching of Industrial Robot Technology Practice Course," *Education and Social Work*, vol. 1, no. 2, pp. 185-194, 2025.
5. I. D. O. Velasco, and O. A. V. Albán, "Virtual Reality platform for Cartesian manipulation of digital twin in a UR3 robot," *Ingeniería y Competitividad*, vol. 27, no. 1, 2025.
6. T. I. Erdei, R. Krakó, and G. Husi, "Design of a digital twin training centre for an industrial robot arm," *Applied Sciences*, vol. 12, no. 17, p. 8862, 2022.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of the publisher and/or the editor(s). The publisher and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.