Journal of Contemporary Educational Research, 2024, Volume 8, Issue 12
http://ojs.bbwpublisher.com/index.php/JCER
ISSN Online: 2208-8474
ISSN Print: 2208-8466

Exploration of Teaching Practices in the ROS Robot Programming Practice Course

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Abstract: The course ROS Robot Programming Practice is designed to equip students with both the foundational principles and practical applications of the Robot Operating System (ROS) through structured instruction and hands-on exercises. This paper summarizes the course's pedagogical approach and the insights gained from its implementation, focusing on key areas such as the practical teaching platform, instructional system, teaching methods, and evaluation mechanisms. The practical teaching platform incorporates robotic arms and mobile robots, along with commonly used sensors, to engage students and stimulate their interest in robotics. A well-structured teaching system is employed, guiding students through a series of experiments—ranging from basic tasks to modeling and simulation experiments, sensor experiments, mobile robot tasks, robotic arm exercises, and comprehensive project practices. Regarding teaching methods, a blended learning approach and progressive instructional model are utilized to ensure active student participation. This approach follows a logical progression, starting with fundamental ROS knowledge, advancing to robot applications, and culminating in comprehensive project-based practice. In terms of evaluation, a dual approach combining process and outcome assessments is employed, ensuring that students' performance is evaluated comprehensively through various metrics.

Keywords: Robot; Robot Operating System; Teaching practice

Online publication: December 31, 2024

1. Introduction

The Robot Operating System (ROS) is an open-source middleware framework designed for robotics, offering a range of functions typically found in traditional operating systems, such as hardware abstraction, low-level device driver control, execution of shared functionalities, inter-process communication, and management of software packages. ROS is widely utilized across academia, industry, education, and development. In academic research, it is extensively used for algorithm development and as an experimental platform, supporting areas such as path planning, visual recognition, and machine learning. In industrial automation, ROS is employed to control robotic arms and automation systems, enhancing manufacturing efficiency and optimizing goods handling and sorting in warehousing and logistics. Additionally, ROS plays a critical role in sectors such as service robots, medical robots, autonomous vehicles, and drones, enabling autonomous navigation and real-time monitoring [1-3].

In education, ROS serves as a valuable tool for teaching robotics technology, while its integration with IoT devices facilitates automated control in smart home environments. Through simulation tools like Gazebo, developers can test robots in a virtual environment, minimizing the risks associated with real-world testing. The robust community and open-source ecosystem of ROS foster collaboration, allowing developers to share and reuse code, thus accelerating the advancement of robotics technology.

Overall, ROS has become a foundational standard in robotics, valued for its flexibility, modularity, and strong community support. Whether in research, education, or industrial applications, ROS provides essential tools and frameworks for building complex robotic systems, driving progress in robot technology.

2. ROS robot practice teaching platform

In previous robot practice teaching processes, students often reported the absence of a comprehensive course and practice platform for systematic learning of ROS. To enhance the robot curriculum system, the construction of the ROS robot practice teaching platform began in 2021, and the course ROS Robot Programming Practice was established in 2022 to address the educational needs of undergraduate students.

The ROS robot practice teaching platform provides students with a hands-on environment for learning ROS. Students can initially grasp ROS and robot operation, understand the components of robot systems, comprehend the process of implementing control algorithms, and learn the working principles of sensors and actuators. Additionally, the platform covers robot 3D simulation modeling, navigation control, and robotic arm control technology. It reinforces students' understanding of fundamental mathematics, computer systems, and programming theories, and trains them to apply their knowledge to engineering practice. This enables students to master the design and analysis of robot systems, cultivate independent learning and lifelong learning skills, and continuously explore and track advancements in ROS technology.

The ROS robot practice teaching platform is designed with extensibility in mind, encompassing a robotic arm platform, a mobile robot platform, and a sensor platform [4-6].

(1) Sensor platform: Sensors are crucial for robots to interact with their environment. Through sensors, robots gather information about themselves and their surroundings, facilitating task planning and execution. In this course, based on the RealSense D435i depth camera and LiDAR, students study the application of sensors in robot motion control.

(2) Robotic arm platform: As illustrated in **Figures 1(a)** and **1(b)**, the course utilizes collaborative robots UR5e and DR6 as experimental platforms. Prior to this practical course, students complete foundational robotics courses. Using the UR5e and DR6 robotic arms, students engage in kinematic analysis, trajectory planning, and visual grasping exercises under ROS.

(3) Mobile robot platform: As depicted in **Figure 1(c)**, students use the RIKIBOT and EAI mobile robots as platforms. The ROS environment for the mobile robot platform is pre-configured, allowing students to understand robot system components, control algorithm implementation, sensor and actuator principles, and master tasks such as map building, autonomous localization, and path planning in mobile robot motion control.

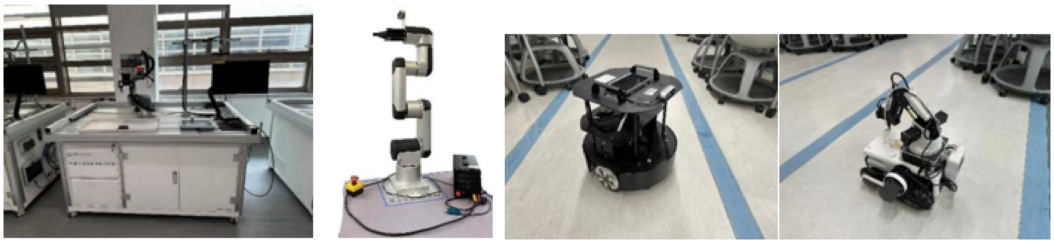

Figure 1. Innovation practice course hardware platform

3. ROS robot practice teaching

3.1. Robin Hendrick's view on blended learning

Based on the hardware resources of the ROS robot practice teaching platform and the practical application of ROS, a comprehensive ROS robot practice teaching system has been constructed. This system aims to maximize the use of experimental equipment and enhance its teaching value. Leveraging the openness and strong extensibility of ROS, the system broadens the application scope of related knowledge, creating a complete robot practice framework and enabling ROS robot hybrid practice teaching at different levels for students across various grades and majors.

As shown in **Figure 2,** the ROS robot practice teaching system comprises a ROS-based robot practice innovation platform, which includes ROS basic experiments, modeling and simulation experiments, sensor experiments, mobile robot experiments, robotic arm experiments, and comprehensive project practices. The practical teaching process primarily focuses on student practice exercises, supplemented by teacher guidance. The teaching follows a developmental path from basic knowledge acquisition to robot application, culminating in comprehensive project practice using ROS as the software platform for robot control.

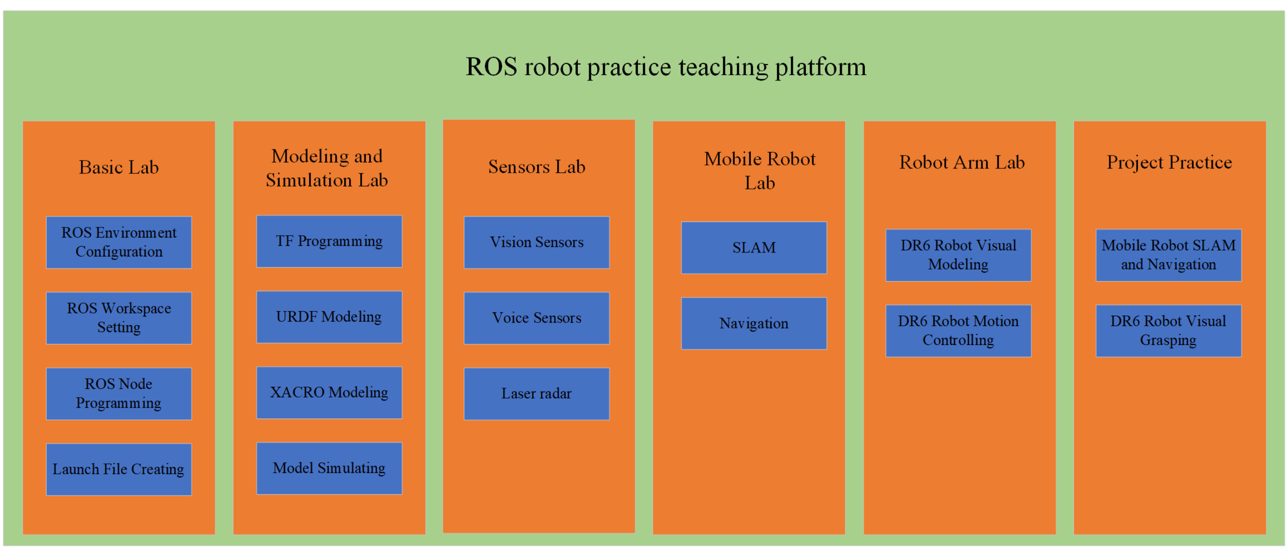

Figure 2. ROS Robot Practice Teaching Platform

The basic knowledge of ROS includes:

ROS basic experiments: This section covers the ROS environment configuration experiment, ROS workspace experiment, ROS node programming experiment, and launch file creation experiment.

Modeling and simulation experiments: This includes TF programming, URDF model creation, XACRO model creation, and model simulation experiments.

Sensor experiments: These comprise visual sensor, speech sensor, and LiDAR experiments.

Through these foundational studies, students can master the operational mechanisms of ROS, utilize ROS for programming and 3D modeling simulation, and establish a solid foundation for subsequent robot control.

The robot application section primarily includes mobile robot and robotic arm experiments. Students use the mobile robot and robotic arm experimental platforms to complete SLAM experiments, robot navigation experiments, DR6 robotic arm visualization modeling experiments, and robotic arm motion control experiments. These hands-on experiments consolidate students' ROS basic knowledge and provide an experimental platform for theoretical study and verification.

The comprehensive project practice section includes:

SLAM and navigation of mobile robots: Students engage in comprehensive practice projects related to mapping and navigation.

Visual grasping of mechanical arms: This involves comprehensive practice in visual grasping tasks.

The final part of the course is dedicated to comprehensive project practice, aimed at guiding students through project-based learning. This allows students to autonomously decide on task completion methods, solve engineering problems, and fully cultivate their practical skills.

3.2. ROS robot practice teaching mode and methods

Following the context of learning ROS basic knowledge, robot applications, and comprehensive project practice, the teaching mode of the ROS robot experiment teaching system is depicted in **Figure 3**. The ROS robot practical teaching described in this article is applicable to professional fields such as robotics engineering, automation, and mechanical engineering. Currently, the ROS Robot Programming Practice course has been introduced for automation and mechanical engineering majors to facilitate the practical teaching of ROS robots.

3.2.1. ROS basic theory learning

The task of learning the basic theory of ROS involves understanding the current development status of ROS, familiarizing oneself with the basic operations of the Ubuntu system, and mastering the file system, computer graphics, community frameworks, as well as ROS communication mechanisms and common components. Students should gain proficiency in creating ROS workspaces and packages, understanding communication methods in ROS, the working mechanisms, and the overall compilation process of ROS packages. Additionally, learners need to understand common robot simulation tools and become familiar with ROS visualization tools like rqt and Rviz, as well as the simulation environment Gazebo.

In terms of mobile robots, students should understand the types, composition, and application scenarios of these robots. They must master spatial coordinate transformation within ROS, as well as sending and reading robot joint and state information. Students will also learn how to build an entire mobile robot system, including using URDF for 3D modeling in ROS, converting URDF files to XACRO files, and performing simulations in Gazebo.

Further, students will explore the practical applications of ROS vision, including acquiring 2D and 3D image data, camera calibration methods, face recognition, object tracking using OpenCV, and QR code recognition. They will also delve into the application of ROS for deep learning and machine speech, learning to use common speech function packages such as iFLYtek's SSDK for Chinese speech recognition, speech dictation, synthesis, and speech assistants.

Lastly, students will become familiar with configuring laser radar environments, reading data, and establishing the spatial relationship between the laser radar and the robot.

3.2.2. Robot control and practice

After learning the basic knowledge of ROS, using ROS nodes to control robots becomes a key aspect of practical robot teaching. It is essential to set up robot motion control experiments specifically designed for students, using ROS as the software platform. By combining various robot application scenarios, students can conduct experiments with mobile robots and manipulators to deepen their understanding of ROS's basic concepts, operation mechanisms, and programming frameworks, ultimately mastering the use of ROS to control robot movements.

For mobile robots, multimedia instruction on SLAM technology and autonomous navigation is necessary. Mobile robots should meet specific hardware and sensor requirements to achieve autonomous navigation. Students should familiarize themselves with the application of SLAM packages such as gmapping, hector_SLAM, cartographer, and ORB_SLAM in ROS, using these tools to construct maps. They must master the configuration and overall framework of the ROS navigation package. By utilizing the navigation package, students can complete autonomous navigation tasks for mobile robots within constructed environment maps. This will be followed by practical sessions where students receive on-site guidance to complete SLAM map construction within a laboratory environment under ROS, and carry out autonomous navigation tasks using the constructed maps.

After learning how to build maps and navigate with mobile robots, the focus shifts to the study of MoveIt!, using the UR5e robot as an example. MoveIt! is a package for motion control of robotic arms under ROS, encompassing motion planning, kinematics, operation control, and collision detection. The system structure of MoveIt! includes a User Interface, move_group, ROS Param Server, and external robot components. Through the 3D visualization platform Rviz, students can perform operations with MoveIt!, including visualization modeling of the robotic arm, kinematic solutions, and motion planning. Once familiar with MoveIt!, students will be guided to communicate with the UR5e robot, using MoveIt! to perform inverse kinematic solutions and motion planning tasks.

3.2.3. Research and innovation project practice

Currently, there is an increasing emphasis on cultivating students' innovative and practical skills. Students are actively participating in various types of robot competitions. In the field of robot experiments and teaching, there is a growing trend towards personalized and comprehensive practical projects. By combining the application of ROS in mobile robot navigation and manipulator grasp task planning, guided by scientific research and comprehensive projects, students engage in practical projects derived from real-world applications of mobile robots and manipulators.

Students work in groups of 3–5 to complete final comprehensive projects, receiving well-rounded training in literature review, proposal development, environment configuration, experimental verification, project demonstration, and defense. This approach aims to cultivate students' engineering skills and foster innovative practical skills.

The personalized comprehensive practice in the course includes integrated practice tasks, such as item transportation in indoor environments and vision-based material sorting projects, which correspond to the tasks of mobile robots and robotic arms. In the integrated practice of item transportation, students learn and apply tools such as gmapping, cartographer, and other navigation packages to complete transportation tasks within a scene. In the vision-based material sorting project, students configure the RealSense camera environment, calibrate the camera, and perform hand-eye calibration between the camera and the robotic arm. They use the camera to identify and locate targets, ultimately enabling the robotic arm to grasp and sort materials.

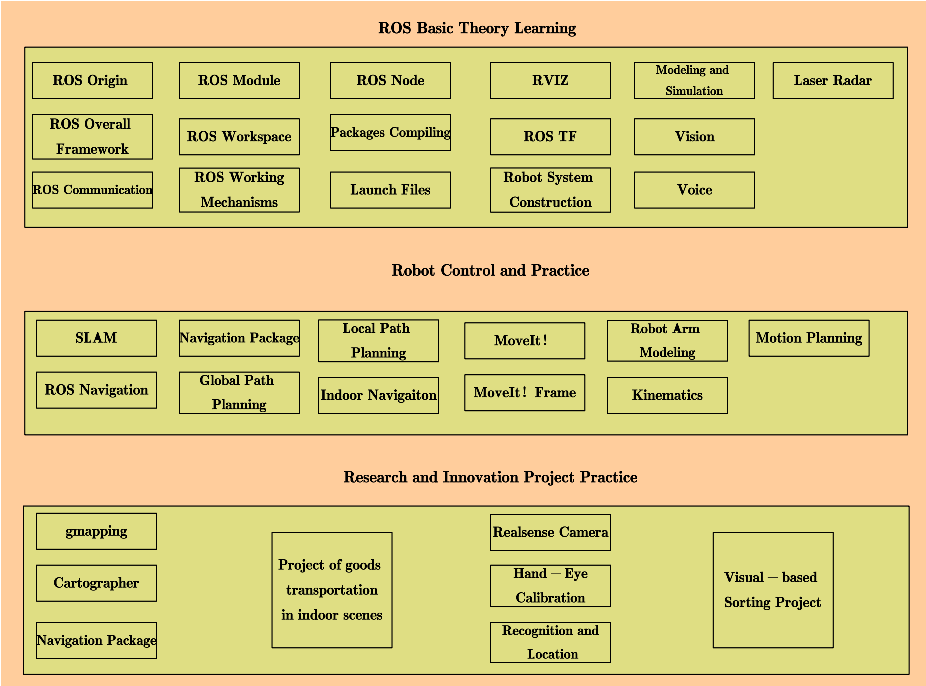

Figure 3. ROS robot practice teaching mode and methods

4. Assessment and evaluation

The ROS Robot Programming Practice course focuses on enhancing students' professional knowledge and innovative practical skills. It aims to guide students in improving their independent learning and comprehensive abilities through a well-designed course assessment and evaluation mechanism. The course seeks to cultivate students' practical engineering skills, assessed through assignments, experimental reports, comprehensive practice reports, and PowerPoint presentations. The assessment process emphasizes students' hands-on abilities, critical thinking, collaborative skills, and communication proficiency.

In the ROS basic theory learning and robot control practice sessions, students are evaluated through assignments and lab reports. These assessments help students quickly grasp the basic knowledge points, operating mechanisms, core functions, and common software tools of ROS through theoretical coursework, assignments, and experiments.

In the personalized comprehensive project practice section, a combined project involving mobile robots and robotic arms is arranged. During this practical process, students work in groups to complete the given project, fostering their engineering skills, teamwork abilities, and communication skills. Upon project completion, students participate in a project defense, presenting their work in detail, showcasing the results, and answering questions from the instructor.

5. Analysis of teaching effectiveness

Since the inception of the ROS Robot Programming Practice course in the fall semester of 2021, a targeted experiment teaching segment has been offered for students with a weak foundation in ROS, in conjunction with undergraduate robotics and comprehensive robot course design. Over three teaching cycles, the course has enrolled more than 100 students and has garnered wide acclaim. The course successfully enhances students' practical operation skills and engagement through a blend of theory and practice, project-driven learning, and extensive teaching resources and practical equipment. The overall teaching effectiveness has been significant. By focusing on ROS robot practice, the course effectively enhances students' innovation and practical skills, providing substantial support for their future project endeavors.

Disclosure statement

The authors declare no conflict of interest.

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