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Virtual Experiments Design for Robotics Based on V-REP

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Abstract. Compared with traditional robot laboratory, virtual robot laboratory integrates programming, modeling and controlling, which can assist related learning of robot courses more efficiently and directly under the condition of saving time and equipment cost. A concept of virtual robotics laboratory based on virtual robot platform V-REP is proposed in this paper. The laboratory is divided into coordinate transformation, positive and inverse kinematics, dynamics and trajectory planning. At the same time, virtual teaching tasks of comprehensive course design for robotics is also proposed to improve students' capacity for designing virtual robots comprehensively and improve teaching quality.

1. Introduction
With the advent of the era of artificial intelligence and rapid growth of robotics, increasingly jobs are being replaced by robots. Robots will accelerate to improve social productivity in several future years to create efficiency and convenience for human life in the future.

In recent years, more and more undergraduate colleges start to set up related majors of robots to satisfy great demands of all walks of life on talents in the aspect of robots. However, as robot equipment is relatively expensive and teachers are undertrained, it is difficult for many colleges to set up a robot experiment course. Aimed at this problem, plenty of robot simulation software is developed, such as MATLAB Robotics Toolbox [1], RoboAnalyzer[2], RoKiSim[3], ARTE[4], and others. There are also many virtual robotics laboratories developed for robot learning, such as a virtual experiment framework of robotics based on Qt and Ogre [5], and ROBOLAB based on Java[6]. The numerous software is few designed for robotics basic knowledge teaching. Some software for teaching and learning are lack of systemic and completeness. The biggest difficulty of robotics teaching at present is how to show mathematical physics meanings of these concepts clearly and combine theoretical knowledge and experimental courses. V-REP is a virtual simulation platform of robots developed rapidly in recent years. Although it does not have direct teaching functions, its abundant expansion capability provides a better tool for us.

A concept of virtual robotics laboratory based on V-REP is proposed in this paper, which explains all basic parts of robotics systematically. It can help students learn and understand basic knowledge concepts of robots better and quickly, thus improving teaching quality of robotics.

2. V-REP and Virtual Robotics Laboratory Architecture

2.1 V-REP

V-REP is a strong robot 3D integrated development environment, which has several universal calculation modules (inverse kinematics, physics/dynamics, collision detection, minimum distance calculation, path planning), distributed control architecture (control scripts of unlimited number, thread or non-thread), and several extension mechanisms (plug-in, client application programme and so on.) [7]. It provides multiple functions and can make integration and combination easily by detailed API and script function.

2.2 Robot model

Some typical robot arms are adapted for robot model of virtual robotics laboratory. Only arm robots are involved and mobile robots are not involved in initial stage. Then it is considered to add related parts of mobile robots in subsequent plans. Model of virtual laboratory mainly include palletizing robot arm, SCARA, DELTA, Puma560. Teachers and students also can use model in V-REP or customize models belonging to them. Plan of virtual experiment is mainly introduced and discussed by 3-DOF robotic manipulator in this paper.

The prototype of the manipulator is from ABB palletizing robot. Reconfiguration design is implemented aimed at robotics teaching. The experimental manipulator mainly includes a workbench and mechanical arm. The experimental scene of the manipulator is mainly used for picking and placing and writing or drawing. The manipulator is a typical 3-DOF series mechanical arm shown in Figure 1, which has strong representation in primary learning of robotics.

Figure 1. 3-DOF robotic manipulator

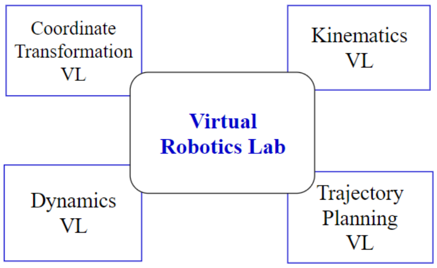

Figure 2. The architecture of virtual robotics laboratory

2.3 The architecture of Virtual Robotics Laboratory

The whole virtual laboratory of robotics is constituted by multiple V-REP document assembly. The contents include important basis chapters in robotics, include coordinate transformation, kinematics, dynamics, trajectory planning. V-REP is a platform supporting multiple systems. The whole software has small capacity and is easy for installation. Document of V-REP is generally several hundred to thousands of KB, which can be used flexibly. These documents can be linked to all parts of textbook respectively and uploaded to cloud for downloading and use by teachers and students in future supporting textbooks. The structure of the whole laboratory is shown in Figure 2.Each laboratory basically involves important knowledge points of the part of robotics. Table 1 shows details.

Table 1. Virtual labs and basic knowledge of robotics

Virtual Lab	Coordinate transformation laboratory	Kinematics laboratory	Dynamics laboratory	Trajectory planning laboratory
Main knowledge concepts	Coordinate transformation Homogeneous transformation Homogeneous transformation matrix Euler Angles Representation RPY Angles Representation Axis / Angle Representation	D-H Parameters Forward Kinematics Inverse Kinematics Velocity Analysis	Inverse Dynamics Forward Dynamics Equations of Motion Euler-Lagrange Formulation Newton-Euler Formulation	Joint Space Planning Cartesian Space Planning Point-To-Point Control Continuous Path Control

Each subsidiary virtual laboratory is an independent file (Figure 3). The interface is designed by OpenGI. Script programming language LUA is adopted to realize programming. LUA programming does not have much syntax requirements and is ideal for robot beginners to implement algorithms. Path planning plug-in OMPL of the robot arm is also involved in path planning laboratory.

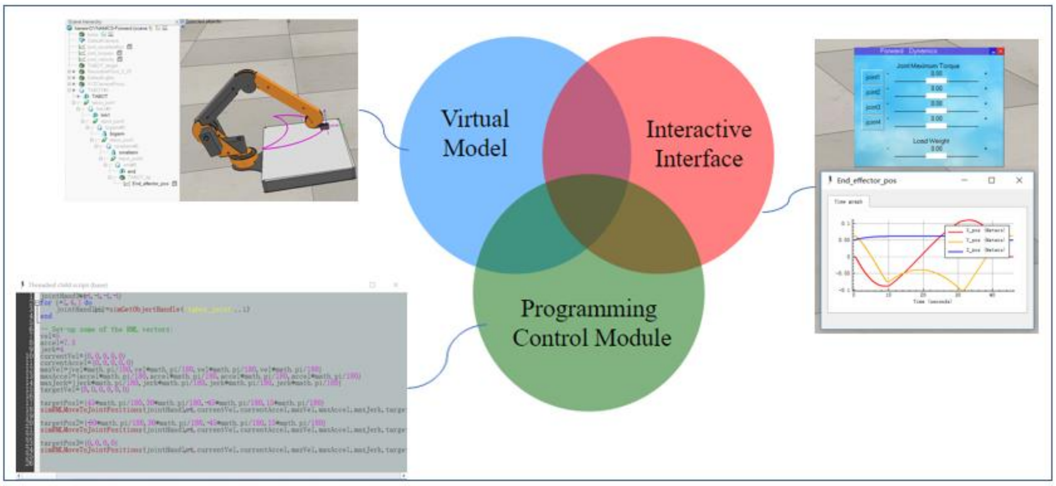

Figure 3. Structure of each virtual robotics laboratory

2.4 Application of virtual robotics laboratory

Application of virtual robotics laboratory is mainly divided into four phases. Each phase is aimed at different teaching purposes from the shallow to the deep to improve students' understanding of robotics and flexible application of basic knowledge step by step, as shown in Figure 4.

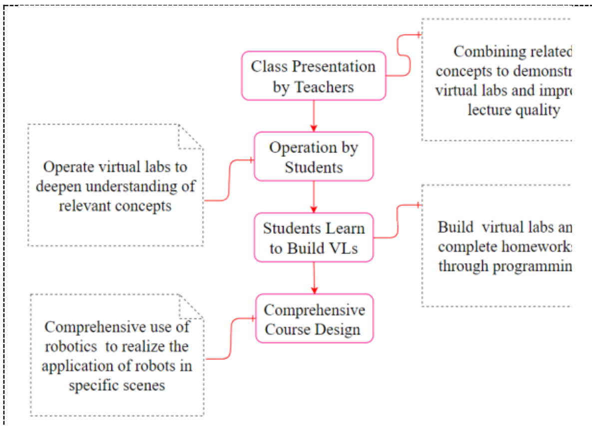

Figure 4. Application of virtual robotics laboratory

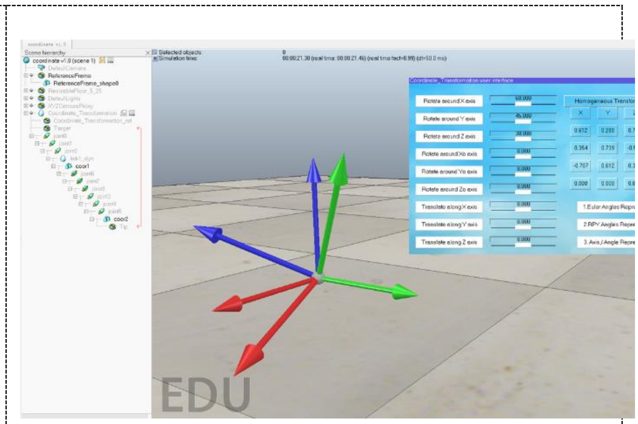

Figure 5. The interface of the coordinate transformation virtual lab

3. Coordinate transformation Virtual lab of robotics

3.1 Introduction to Virtual laboratory of coordinate transformation

Virtual laboratory of coordinate transformation of robotics is composed of a series of coordinate frames and joints. Rotation and translation of coordinate frames are realized by adding rotating joints and prismatic joints between two coordinate frames. OpenGI embedded in V-REP is adopted for UI interface to control coordinate frame model and calculate homogeneous coordinate transformation matrix. Virtual laboratory of coordinate transformation assists students in learning mathematical foundations of coordinate transformation of robotics by vivid and immersing three-dimensional scene, simple and direct operation and quick matrix calculation. The interface of the laboratory is shown in Figure 5. As coordinate transformation has different parameterization method, 3 kinds of different calculation methods of homogeneous coordinate transformation matrix are set up here, respectively Euler angle representation method, RPY angle representation method and spindle/angle representation method. Programming module is realized by script document. The main function is to realize interaction between coordinate model and UI: including data transmission, matrix calculation and so on. The coordinate transformation virtual laboratory can perform various translation, rotation, and compound transformations. The rotation transformation can rotate around the current coordinate frame as well as around the fixed coordinate frame, as shown in figure 6.

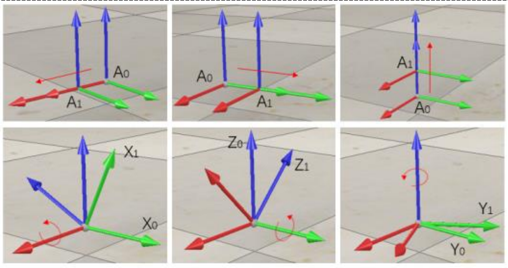

Figure 6. Elementary translations and rotations demonstration

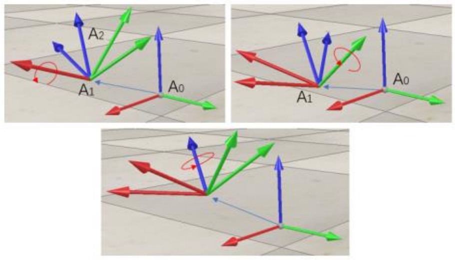

Figure 7. Compound transformation demonstration

Three upper pictures in Figure 6 represent translation along the X axis, Y axis and Z axis respectively, three lower pictures represent rotation around X axis, Y axis and Z axis of current coordinate frame respectively. Visualization and dynamization of coordinate transformation can be realized only by dragging corresponding slider (or entering some numerical values). The compound transformation is shown in Figure 7.

3.2 Teaching demonstration of coordinate transformation

In order to test the experimental results, a coordinate transformation based on the PRY angle representation is shown here:

1.Rotate 60° along the X -axis of the fixed coordinate system (the result is the coordinate frame X1Y1Z1)

2. Rotate 45° along the Y-axis of the fixed coordinate system (the result is the coordinate frame X2Y2Z2)

3. Rotate 30° along the Z-axis of the fixed coordinate system (the result is the coordinate frame X3Y3Z3)

Start the simulation by typing 60°, 45°, and 30° in Rotate around X axis, Rotate around Y axis, and Rotate around Z axis. You can see the changes in Figure 8.

After that, click 2.RPY Angles Representation and the homogeneous transformation matrix will be immediately calculated in the UI as shown in Figure 9.

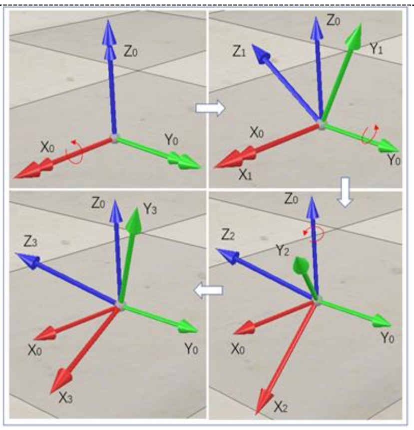

Figure 8. Teaching demonstration

Figure9. Homogeneous transformation matric calculation

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4. Kinematics Virtual Lab

4.1 Introduction to kinematics virtual lab
Kinematics is one of the very important basic contents of robotics. Planning of kinematics will directly influence the later dynamics modeling and trajectory planning. In traditional teaching, robotics theory knowledge is usually only explained through textbooks, which is difficult to master these concepts quickly for students. Virtual laboratory of kinematics displays typical robots by visual models so that teachers can show forward and inverse kinematics concepts through simple operations. Students can understand quickly and establish kinematics concept thinking quickly at the same time through the display of D-H coordinate, real-time calculation of matrix transformation and explanation of simple robot algorithm. Robotic kinematics mainly includes forward kinematics and inverse kinematics. In the virtual laboratory, these two situations can be demonstrated separately by the operation of the slider. In the whole process, the D-H coordinate system where all joints are located can also be displayed, and the understanding of kinematics can be deepened through coordinate transformation. After demonstrating the virtual lab, the teacher can explain the corresponding forward and inverse kinematics algorithm through the script.

4.2 Teaching demonstration of kinematics virtual lab

4.2.1 Forward kinematics: Joint positions can be changed by dragging slider in three joints respectively (or inputting angles value through textbox). Positions of end-effector are calculated under drive of script program in real time and manipulator will move to corresponding positions at the same time. As shown in Figure 10, the three joints of the robot arm rotate 30°, 15°, and -15°, respectively.

4.2.2 Inverse kinematics: Set up the robot end-effector position by dragging the X, Y, and Z sliders (or entering the Cartesian space coordinates via the textbox). Then, the joint position will be calculated in real time by the inverse kinematic algorithm of the script program. At the same time, the robot will move to the corresponding posture. The Figure 11. shows the end-effector moving to Cartesian coordinates (0.11, -0.03, 0.04).

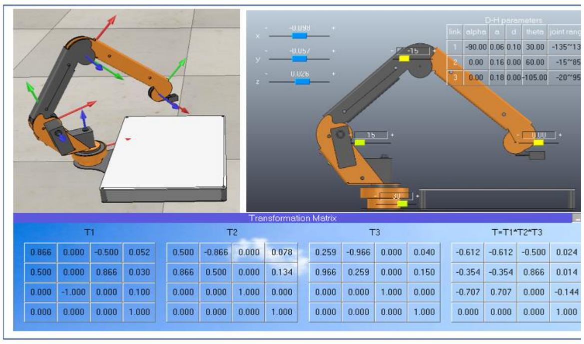

Figure 10. Forward kinematics demonstration

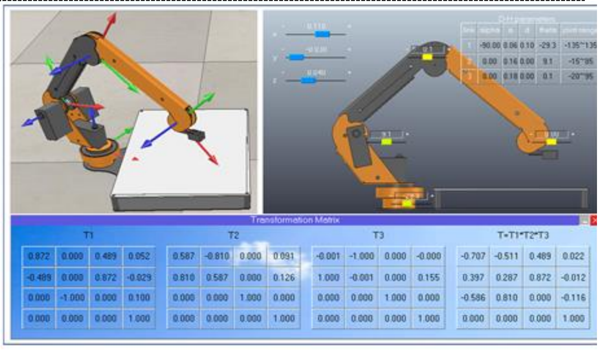

Figure 11. Inverse kinematics demonstration

5. Dynamics Virtual Lab

5.1 Introduction to dynamics virtual lab
The robot's motion characteristics under the influence of various joint forces and moments are studied in dynamics. Firstly, the trajectory control accuracy of robotic manipulator or end-effector depends on the accuracy of dynamics model; secondly, when the robot is constructed, its motion control characteristics can be simulated using dynamics; conversely, results of robot dynamics research can provide basis for robot structure optimization. Similar to kinematics, there are forward and inverse dynamics in robot dynamics. Forward dynamics studies the law of motion of robotic end-effector under the action of various joint forces and moments, and inverse dynamics studies the required joint

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control forces and torques for a given motion trajectory. It can be seen that inverse dynamics plays a key role in real-time control of robots. Virtual laboratory scene of dynamics mainly includes robot model, UI interface, program script and some graphs. Where UI interface mainly realizes maximum torque of controlling all joints and weight of controlling object. Position of each end-effector, all joint angular velocities, joint angular accelerations, torque and other parameters are displayed in the graphs. Dynamics algorithms are implemented in program scripts. Here are two dynamic algorithms for students to learn: Euler-Lagrange formulation and Newton-Euler formulation.

5.2 Teaching demonstration of dynamics virtual lab

It is usually difficult for students to understand the meaning of dynamics analysis in the teaching of robotics. They usually think that kinematics can control manipulator, so why still should learn dynamics. The demonstration of the virtual dynamics laboratory can enable students to have a clearer understanding of dynamics.

5.2.1 Inverse dynamics: In inverse dynamics, firstly, trajectory of end-effector is needed to be set up in inverse dynamics, then joint positions, velocities, accelerations will be calculated through inverse dynamics. Torques and forces of each joint required in different position will be calculated by inverse dynamics and shown in different graphs with curves. Maximum control force or torque of joint required by us can be obtained by graphs, which can provide reference for robot structure design. The Figure 12 is two examples with a track of straight line and a circular arc, and recorded joint positions, velocities, accelerations and joint torques are shown in the graphs.

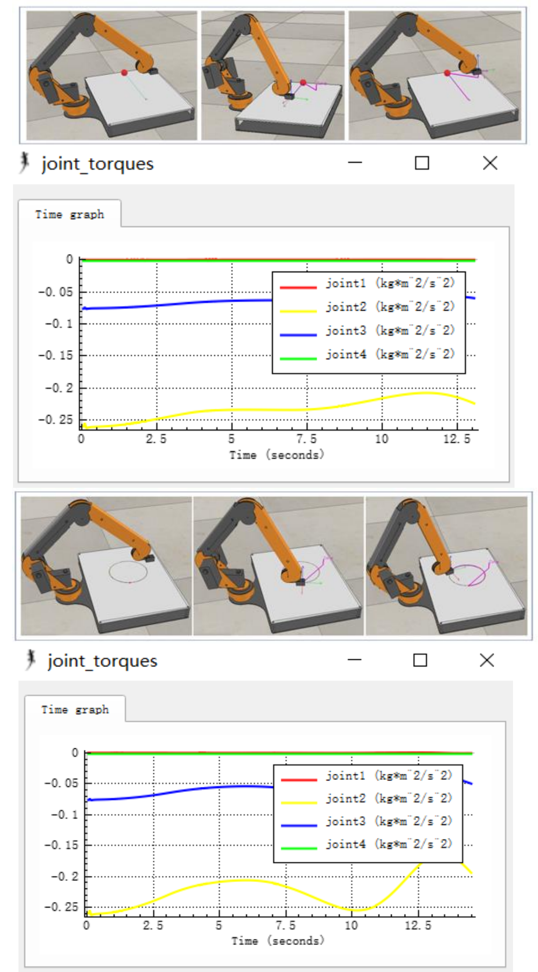

Figure 12. Inverse dynamics demonstration

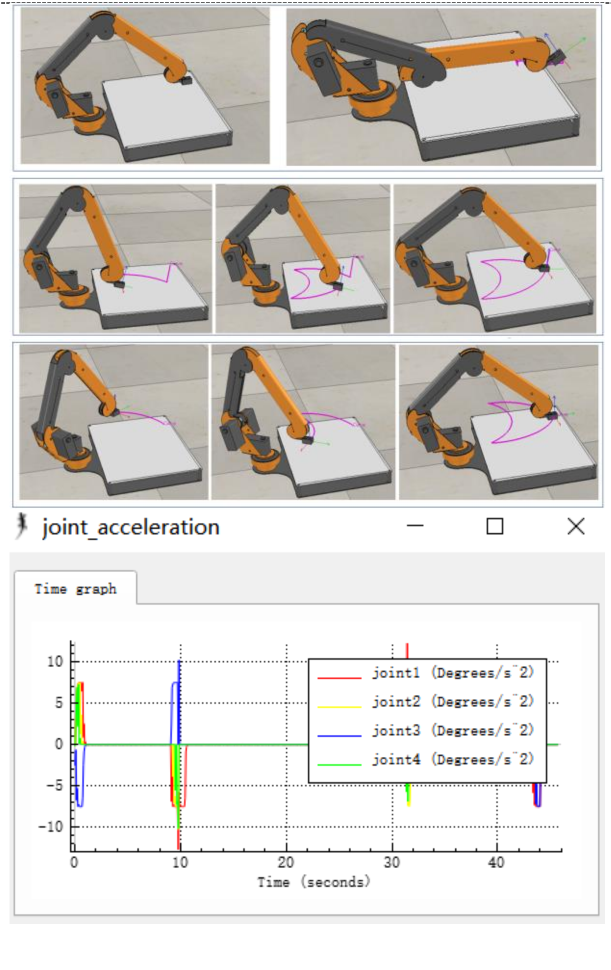

Figure 13. Forward dynamics demonstration

End-effector movement condition can be observed under the condition that different joint torques are given for manipulator operation after above virtual experiment.

5.2.2 Forward dynamics: Maximum torque of each joint is set up and movement rules of the end-effector are observed and studied in positive dynamics. Firstly, the torque of all joints is set to be 0 N m, as shown in the Figure13. It can be seen that robot arm will fall down due to gravity. When dragging and increasing maximum torque of each joint, for example 0.1 N m, the end-effector is dragging on the bench. After analyzing the above parameters, it was found that the cause of dragging was mainly due to the insufficient torque of the joint 2. When the joint 2 was set up approximately 0.3 N m, we can observe that the manipulator is successfully operated. Each joint position, velocity, acceleration are calculated and recorded in graphs in the entire procedure(only the joint acceleration is listed here).

6. Trajectory Planning Virtual Lab

6.1 Introduction to trajectory planning virtual lab
Trajectory planning is the description of robots performing tasks in robots. All the previous foundations are prepared for trajectory planning. The trajectory planning virtual laboratory mainly presents related basic concepts by displaying several typical planning methods. Here, the virtual laboratory shows joint space-based trajectory planning and Cartesian space-based trajectory planning. Point to point (PTP) control and continuous path (CP) control are introduced for trajectory control in trajectory planning.

The virtual laboratory for trajectory planning can realize the motion planning of the virtual robot arm through simple programming and operation. In the virtual environment, the end-effector motion trajectory can be displayed, and the position, angular velocity, and angular acceleration of each joint can be graphically displayed. The Author has presented a complicated function of writing and drawing in the form of welded connection, which is a presentation of trajectory planning.

In the virtual laboratory for trajectory planning, we have used kinematic calculation module of V-REP, used and integrated Reflexxes Motion Library type IV C++. Programming is implemented by some simple APIs.

6.2 Teaching demonstration of trajectory planning

6.2.1 Trajectory planning based on joint space: Trajectory planning is performed directly in the joint space without knowing the entire motion path equation. This is accomplished by specifying the joint displacement function of joints in the motion space. In terms of the virtual model for robot Puma560, the terminal trajectory of robot, and positions, velocities and accelerations of joints are recorded respectively in the graphs as follows: The first thing needs to be defined is the initial and final joint position. Three positions are given in the Table 2. the robot will move to a certain position and then back to the initial position. The entire movement is shown in Figure 14.

Table 2. Three Positions

joint	Joint1	Joint2	Joint3	Joint4	Joint5	Joint6
Initial Pos	0°	0°	0°	0°	0°	0°
Pos 1	45°	45°	45°	30°	15°	0°
Final pos	0°	0°	0°	0°	0°	0°

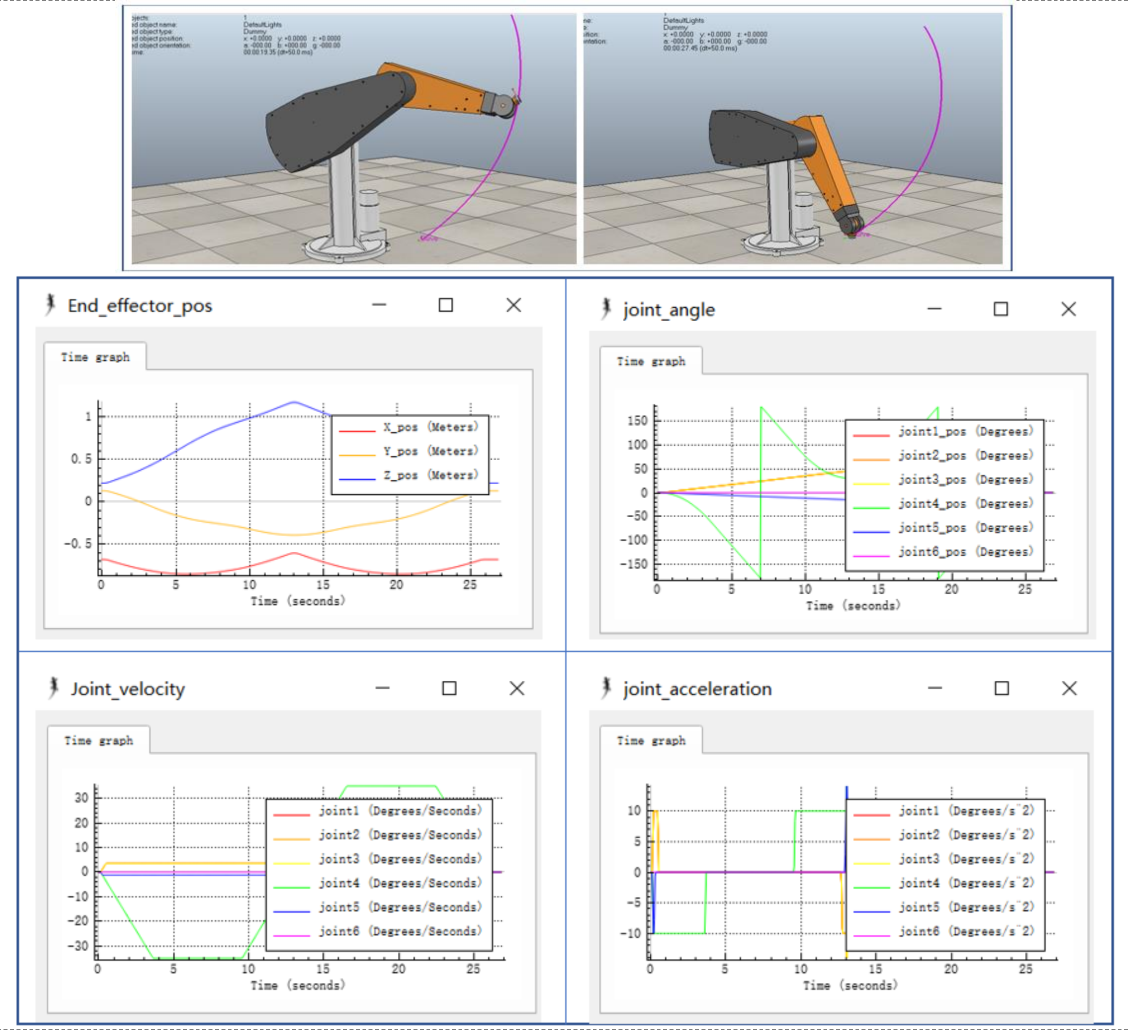

Figure 14. The scene of trajectory planning laboratory for Puma560

6.2.2 Trajectory Planning Based on Cartesian Space: Also known as Orthographic Space Trajectory Planning. The motion path is known, and the key points are converted into joint space by inverse kinematics to control the joint rotation. Trajectory planning of Delta manipulator based on Cartesian space is shown in Figure 15. Pictures show the scenarios of motion along the arched trajectory and arc trajectory.

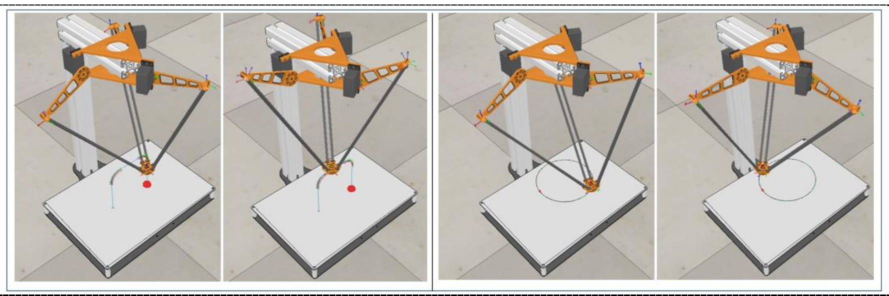

Figure 15. The scene of trajectory planning laboratory for Delta

6.2.3 Point to point control (PTP): The manipulator has to move from an initial to a final joint configuration in a given time; In this case, the end-effector path is of no concern [8]. In the middle of the trajectory, there are only joint geometric constraints, maximum speed and acceleration constraints.

In the trajectory planning virtual laboratory, Dummy can be added as a virtual trajectory point, and then the inverse kinematics algorithm is used to calculate the joints vectors corresponding to the point. As shown in the Figure 16, it is desirable for the robot arm to reach these four positions, but do not care about the intermediate process. Adds the geometric constraints, maximum velocities and acceleration constraints of the robotic joint programmatically. Here, we added a spot weld head to show the trajectory of the tip on the platform. The result was shown in Figure 16.

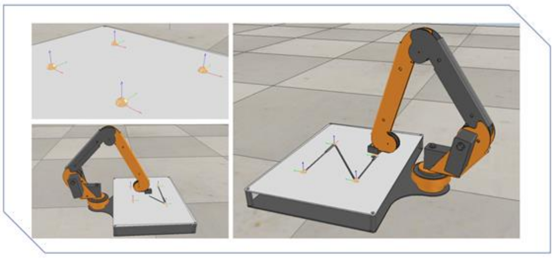

Figure 16. The scene of PTP control

6.2.4 Continuous trajectory control (CP): The end-effector has to follow a prescribed and controlled path within a certain accuracy range in strict accordance with the predetermined trajectory and speed, and it is required that the speed be controllable, the trajectory be smooth, and the movement be performed smoothly and completely. In the trajectory planning virtual laboratory, students can perform continuous path planning by adding a path or generate a continuous path by importing a path file in CVS format. Then, the end-effector is programmed to follow the path movement. The Figure 17. shows generated paths and the motion of continuous trajectory control in the virtual laboratory of trajectory planning.

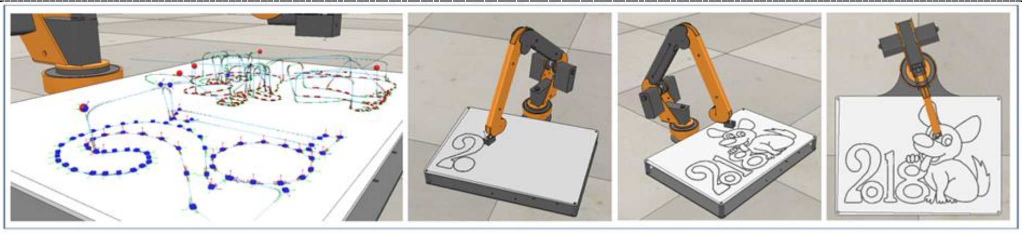

Figure 17. The scene of CP control

7. Robotics Course Comprehensive Design Experiment Plan

In order to test and reinforce students' basic knowledge and primarily develop their comprehensive design capability for the practical robotic application scenario after they have learnt basic courses on robotics, we have proposed comprehensive design of robotics courses, such as implementing cooperation between robot palletizer and conveyor belt to realize pick and place task in assembly line, and robots palletizing. In comprehensive design, overall knowledge framework of robotics will be considered and basic knowledge of each part will be integrated into a design in a way that reinforces basic knowledge, trains the capacity to utilize basic knowledge, and implements high-quality teaching objectives of robotics by the idea learning by doing or learning by projects. Results of comprehensive design of robotics courses of China University of Mining and Technology (Beijing) are shown in Figure 18 and Figure 19.

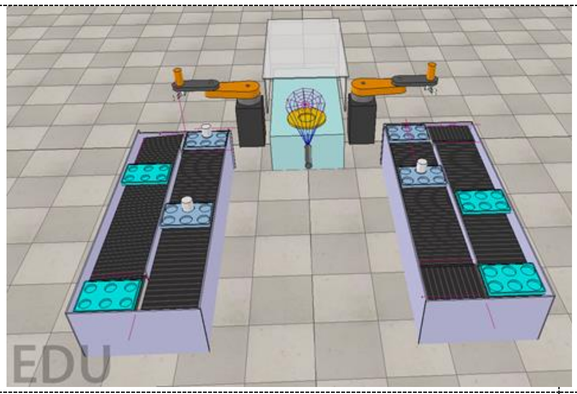

Figure 18. Robotics Course Comprehensive Design

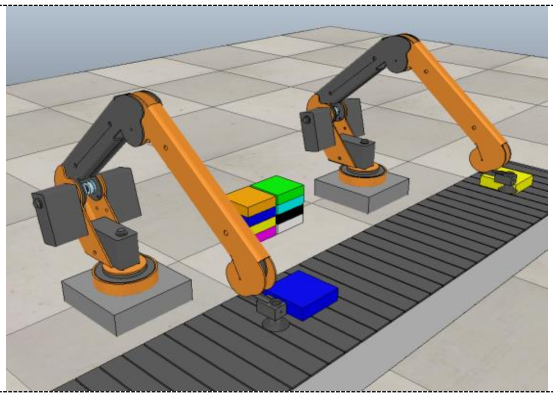

Figure 19. Robotics Course Comprehensive Design

8. Conclusion

In the paper, a planning scheme for V-REP-based robotics teaching virtual experiments was proposed. Main basic knowledge about robotics involved is demonstrated and explained for teaching in the virtual laboratory established by the model of typical manipulators. The robotic virtual laboratory established covers robot arm of palletizer, Puma560, Delta, SCARA and other typical robot arms. It is suitable for primary learning on robotics. The robotic virtual laboratory shows the obscure concepts of robotics in a manner of simple interaction and in the form of virtual simulation. The virtual laboratory will save more funds for experimental equipment for more colleges and universities, save teaching space and improve teaching efficiency. Besides, V-REP is selected as the experimental platform. On the one hand, V-REP has a good modularity function, which can provide convenience for subsequent integrated design and subject research. It is also a good tool for subject research on robots and can provide a good platform for prototype design and algorithm verification to prepare for future scientific research. The extensive expansion capabilities of V-REP will provide more powerful advantages in robot teaching and subject research. The robotic virtual laboratory will also help teachers improve the quality of teaching with more functions and help students learn robotics-related courses.

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