Journal of Contemporary Educational Research, 2023, Volume 7, Issue 4
http://ojs.bbwpublisher.com/index.php/JCER
ISSN Online: 2208-8474
ISSN Print: 2208-8466

Project-Based Teaching in Control Theory Education Based on V-REP: A Cart Inverted Pendulum Case

Chao Liu, Yonghuai Yang, Chengwei Zhang, Shengyi Yang*

School of Physics and Mechatronic Engineering, Guizhou Minzu University, Guiyang 550025, Guizhou Province, China

***Corresponding author:** Shengyi Yang, yangyshy@foxmail.com

Abstract: This paper provides a teaching concept for control theory education based on Virtual Robot Experimentation Platform (V-REP). A cart inverted pendulum virtual physical model is developed on V-REP. Students must analyze, design, and implement a suitable controller for the cart inverted pendulum system using their knowledge of the control theory. Different from traditional experiment and numerical simulation, virtual experiment is safe and less constrained. Moreover, the experiment results are more intuitive and obvious. This study can improve students' interest in learning the control theory and help students understand the relevant content better.

Keywords: V-REP; Inverted pendulum; Control; Education; Virtual experiment

Online publication: April 25, 2023

1. Introduction

In engineering disciplines, the control theory is crucial in helping students analyze dynamic properties and develop a controller to improve the performance of the dynamic system. In order to better understand the ambiguous theoretical control conception and more extensive hands-on experience, the cart inverted pendulum is used as the benchmark for control theory experiments. Then, the control methods, observers, planning algorithms, and advanced sensors can be developed on the cart inverted pendulum via project-based teaching, thus reducing the gap between the theory of control method and practice of control applications.

Many pendulum physical benchmarks are used in control theory education. Several pendulum benchmark systems used in teaching and research have been investigated [1,2], pointing out that inverted pendulum is nonlinear and open-loop unstable. Root-locus analysis, the linear optimal control method, and the complex nonlinear control method can be used. Some advanced control algorithms have been implemented on the inverted pendulum, and the validity and reliability of the algorithms have been verified [3,4].

It is known that the real physical inverted pendulum benchmark increases the cost of control theory education. Some universities have attempted, at their very best, to develop their own inverted pendulum experiment testbed. Besides, some researchers have provided low-cost and open-source inverted pendulum benchmarks. However, the maintenance of that hardware equipment also brings heavy economic burden and is unaffordable for several universities [5].

Moreover, the hardware inverted pendulum experiment testbed requires specified experiment space; in addition, there are limited number of students participating in the experiment and limited experiment time, thereby preventing students from exploring, identifying, and solving problems freely in an inverted pendulum testbed [6].

A popular solution is using a numerical simulation testbed instead of the hardware inverted pendulum experiment testbed [7]. A mathematic model of the inverted pendulum has been deduced, and a numerical simulation has been developed. The numerical simulation relies only on computer and reduces the cost of education. Besides, most numerical simulation programming platforms can be used on personal computers. Hence, students can simulate the results of the inverted pendulum whenever and wherever they want. However, numerical simulation results are mostly number-based and not intuitive for students, especially for beginners. Although the output data are plotted as curves, students cannot explain the actual physical phenomenon with the curves and may find it difficult to explain the reasons for the specific phenomenon. Even worse, numerical simulation requires the knowledge of numerical calculation, such as numerical integration of ordinary differential equations, which are unfamiliar to most undergraduates. Besides, the modeling method is also important to the simulation result.

With the rapid and continuous development of virtual simulation technology, a better solution with virtual simulation can be considered. In a virtual experimentation platform, a virtual physical model can be built and driven like in the physical world [8].

In this paper, we provide an alternative way to build a cart inverted pendulum for experiments of control theory education. We developed a benchmark on V-REP, a popular robot simulator. We then applied a full state feedback control to stabilize the cart inverted pendulum. In the second section, the structure of the pendulum benchmark is described, while the model and control method of the cart inverted pendulum are discussed in the third section. The fourth section shows the simulation result of the system.

2. Cart inverted pendulum benchmark

2.1. Virtual Robot Experimentation Platform

V-REP (now known as CoppeliaSim) is an integrated development three-dimensional (3D) simulator for robots. In the virtual environment, robotic systems including mechanical structure, sensors, and actuators can be modeled rapidly. Besides, the interactive environment components of a robot can be built [5].

With a virtual model, V-REP provides suitable physical engines for dynamic simulations. Students undertaking the control theory course can focus on control methods rather than the numerical calculation of the mathematical model of the cart inverted pendulum. The simulation results based on V-REP can also be displayed through virtual animation instead of a bunch of data. Students can intuitively observe the physical phenomena of the cart inverted pendulum with any actuation.

Furthermore, students can extend various functionalities of the robot on V-REP by using programming languages that are familiar to them, such as C/C++, Python, Java, Lua, MATLAB, Octave, and Urbi. Besides, several programming approaches, such as remote clients, plugins, and ROS nodes, can be used. Thus, students with different programming abilities can freely participate in the experiment [5].

2.2. Virtual cart inverted pendulum model

In order to build a simple cart inverted pendulum system, shapes and joints are used.

Shapes are rigid mesh objects that are composed of triangular faces. The rigid object of robot with arbitrary geometric shape can be built with shapes. Besides, the dynamic characteristics such as mass and inertial matrix can be modified in rigid body dynamic properties.

The cart inverted pendulum is a two degree of freedom system. The cart translates along the track, and the swing pendulum rotates along with the cart. A prismatic joint is used to simulate the translational motion of the cart, and a revolute joint is used to simulate the rotational movement of the swing pendulum. The cart inverted pendulum built with V-REP is shown in **Figure 1**, and the scene hierarchy of the virtual model is shown in **Figure 2**.

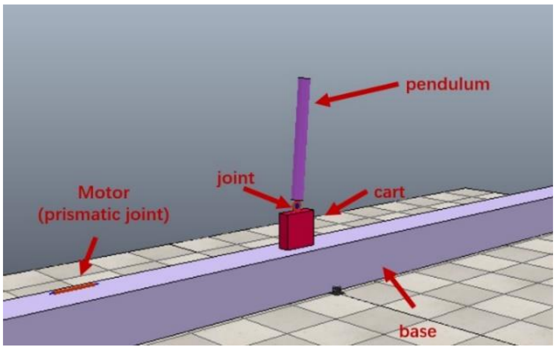

Figure 1. Model of cart inverted pendulum in V-REP

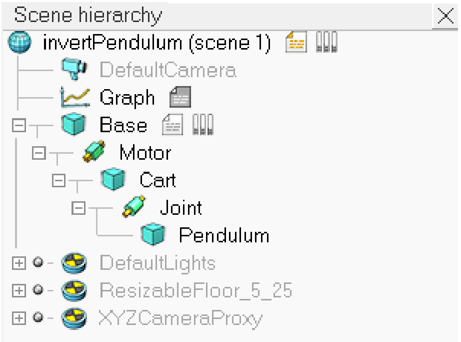

Figure 2. Scene hierarchy of the virtual model

2.3. Control approach of the cart inverted pendulum

V-REP provides two methods to control the cart inverted pendulum: the local approach and the remote approach. With the local control approach, the control entity is internal. The embedded script, add-on, and plugin can be used. The remote approach, by contrast, uses an external control entity via ROS nodes or remote API client. This means that the cart inverted pendulum can also be controlled with ROS or MATLAB.

The embedded script is written in Lua and associated with a single system, such as the cart inverted pendulum built. Considering that many students have C language programming experience, the embedded script is an optimal choice.

In the embedded script, the states of the cart inverted pendulum are provided, and the control force is applied to the mass center of the cart. The students can then concentrate on the controller design with their understanding of the control theory.

3. Teaching method

For a long time, the teaching content of the control theory is mainly about mathematical derivation. Students are taught to obtain the transform function from block diagram, calculate the dynamic behavior, and draw bode plot and Nyquist plot. Even students can analyze and design a controller to improve the performance of the transform function or state equations. They are confused when faced with a real controlled plant with an engineering background instead of an abstract mathematical formula. For those potential control engineers, an experimental benchmark is absolutely necessary.

In view of that, we propose a virtual cart inverted pendulum experimental benchmark based on V-REP. Without the limitation of space and time, students can freely apply their control algorithms to the controller of the cart inverted pendulum. With the intuitive simulation result, they can compare the control results and weigh the advantages and disadvantages of different control algorithms.

More importantly, students can repeatedly apply the key points of the control theory to design a suitable control algorithm for the cart inverted pendulum and master the basic process of engineering controller design and implementation. They can visually compare the control effects of different control algorithms and analyze the effectiveness of the controller from the perspective of different disciplines.

Besides, students are encouraged to analyze the physical phenomena via the theoretical knowledge they have learned. For students with strong learning ability, extended experiment with high complexity requiring multi-disciplinary skills are offered, such as sensor fusion, distributed control, planning, and noise suppression.

According to this teaching method, the principles and theoretical parts of the control theory are taught in class. The verification and application are then applied to the virtual inverted pendulum benchmark. Students may face different cart inverted pendulum systems by setting different parameters, such as mass, inertial matrix, and friction coefficient.

Each cart inverted pendulum control research with different system parameters can be regarded as an independent project for students. Students are required to participate in a comprehensive controller design process, including system modeling, model simplification, system open-loop analysis, controller design, system closed-loop analysis, and controller implementation, as shown in **Figure 3**.

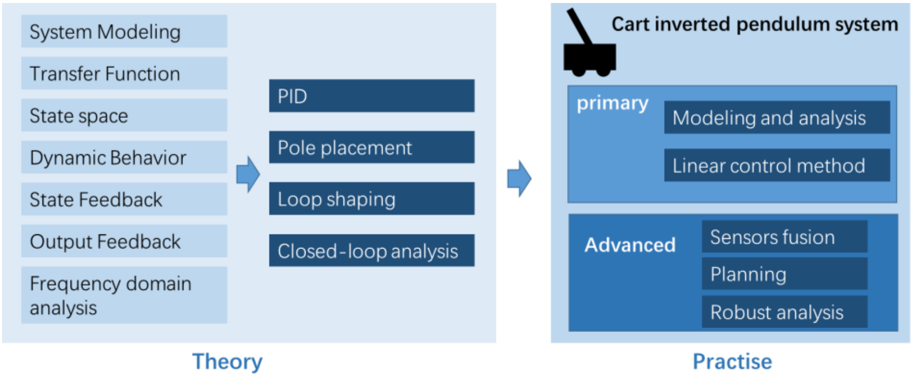

Figure 3. Structure of the teaching method

4. Modeling and control

Consider a cart inverted pendulum system, consisting of a cart with a pendulum rod connected to its mass center, as shown in **Figure 4**.

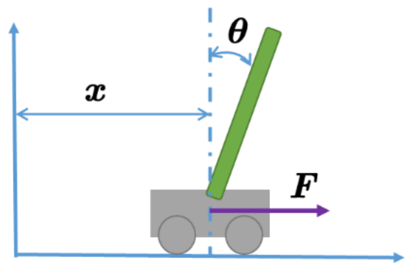

Figure 4. Model of the cart inverted pendulum

The mass of the cart is m_1, while the mass of the pendulum rod is m_2. The distance between the center of the cart and the coordinate's origin is x; θ denotes the rotation angle of the pendulum rod from the vertical axis. The control force F is placed on the mass center of the system. The moment of the inertia of the pendulum rod with respect to the rotation joint is J. The length of the pendulum rod is l. Here, it is assumed that there is no friction in the system.

Then, the velocity of the system is $\dot{x}$, and the rotation speed of the pendulum rod is $\dot{\theta}$. With Lagrange equations, the mathematic model of the cart inverted pendulum is obtained as follows:

$$(m_1 + m_2)\ddot{x} + m_2 \frac{l}{2}\ddot{\theta}\cos\theta - m_2 \frac{l}{2}\dot{\theta}^2 \sin\theta = F \tag{1}$$

$$m_2 \frac{l}{2}\ddot{x}\cos\theta + \left[m_2\left(\frac{l}{2}\right)^2 + J\right]\ddot{\theta}_1 + m_2 g \frac{l}{2}\sin\theta = 0 \tag{2}$$

The cart inverted pendulum system (1) and (2) are coupled and nonlinear. In order to control the system with the linear control method, linearization near the equilibrium position is required. Note that the equilibrium position of the system is $\theta = \pi$. With the assumption that the rotation angle of the cart inverted pendulum stays within the neighborhood of this equilibrium, the linear system is obtained:

$$\left(J + m_2\left(\frac{l}{2}\right)^2\right)\Delta\ddot{\theta} - m_2 g\frac{l}{2}\Delta\theta = m_2\frac{l}{2}\ddot{x} \tag{3}$$

$$(m_1 + m_2)\ddot{x} - m\frac{l}{2}\Delta\ddot{\theta} = F \tag{4}$$

With the linear system (3) and (4), the transfer function of the cart inverted pendulum, $\frac{\Delta\theta(s)}{F(s)}$, $\frac{\Delta x(s)}{F(s)}$, and $\frac{x(s)}{\Delta\theta(s)}$ can be obtained with Laplace transform. More detail can be found in the study by Kafetzis *et al.* [7].

Then, the stability analysis and system open-loop response are asked. After understanding the characteristics of the system, students are required to design their own control system of the cart inverted pendulum with the control knowledge they have learned. For beginners of the control theory, the proportional-integral-derivative (PID) control method is more acceptable. Students are encouraged to obtain the PID control parameters by system closed-loop transfer function analysis.

Although the PID controller is very simple and concise, the cart inverted pendulum control problem remains very difficult for students. The key point is that the experiment phenomena are closely related to the characteristics of the system. It is difficult for students to analyze the phenomena using comprehensive learned knowledge.

5. Experiment results and conclusion

The control experiment is developed on V-REP, the initial rotation angle of the pendulum is $\theta(0) = 5°$, and the initial position of the cart is $x(0) = 0$.

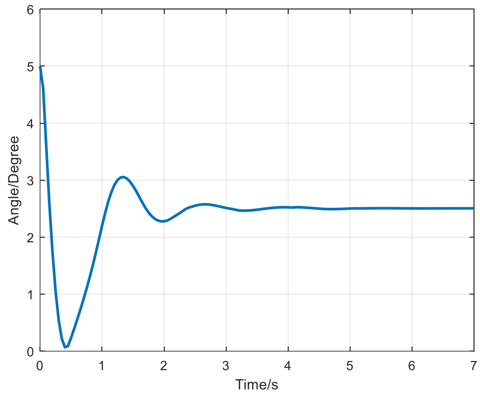

Figure 5. Rotation angle of the pendulum

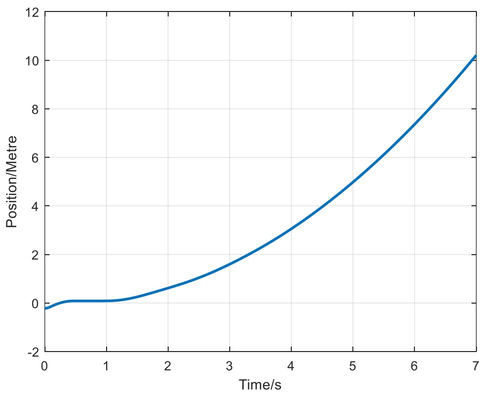

Figure 6. Position of the cart

Figures 5 and **6** provide the result of controller for stabilizing the rotation angle of the pendulum in the cart inverted pendulum. As shown in **Figure 5**, the rotation angle converges to a constant value instead of zero. It seems that the requirement of the control is met. However, the position of the cart continues to increase. The rotation angle is the output state of the system, and the position is the internal dynamics. Even if the output converges, the internal dynamics are in free motion. That is the reason the position of the cart continues to increase.

In order to solve the problem, cascade PID control method should be used. An inner loop controller is used to stabilize the rotation angle of the pendulum to make the angle converge to zero. An out-loop controller is used to make the position of the cart track the desired position trajectory provided. The results of the cascade PID control method is shown in **Figures 7** and **8**.

In fact, the cascade PID control method depends on different time scale in the system. If we want a better control performance of the cart inverted pendulum, full state feedback should be employed.

This experimental process allows students to focus their attention on the control system design and analysis, and the virtual simulation results allow them to visualize the motion of the inverted pendulum of the cart under different control methods. More importantly, students can compare the outputs of different control structures to weigh the advantages and disadvantages of output feedback versus state feedback.

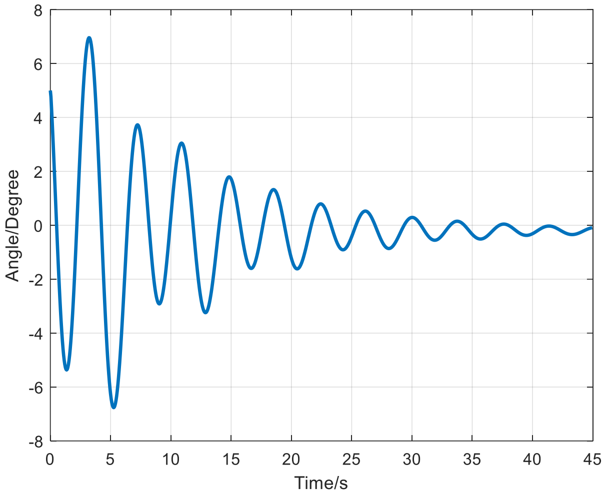

Figure 7. Rotation angle of the pendulum

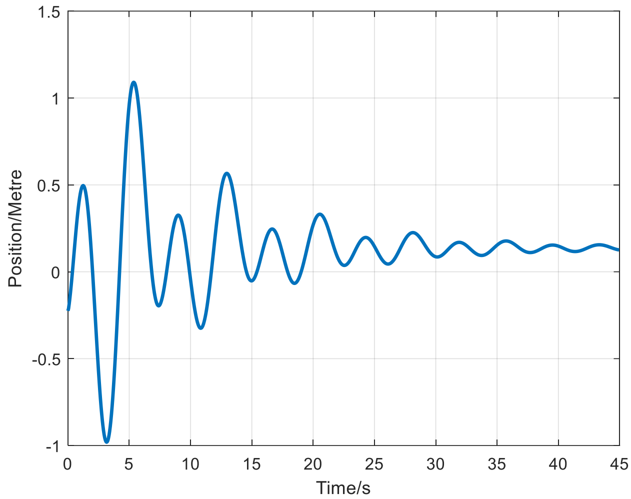

Figure 8. Position of the cart

Funding

This work was supported by the 2021 Higher Education Teaching Reform Research Project of SEAC (No. 221057), 2021 Ministry of Education Collaborative Education Project (No. 202102646007), and 2022 Guizhou Province Gold Course Construction Project.

Disclosure statement

The authors declare no conflict of interest.

References

[1] Boubaker O, 2013, The Inverted Pendulum Benchmark in Nonlinear Control Theory: A Survey. International Journal of Advanced Robotic Systems, 10(5): 233.

[2] Boubaker O, 2012, The Inverted Pendulum: A Fundamental Benchmark in Control Theory and Robotics. International Conference on Education and E-Learning Innovations. IEEE, 2012: 1–6.

[3] Waszak M, Łangowski R, 2020, An Automatic Self-Tuning Control System Design for an Inverted Pendulum. IEEE Access, 8: 26726–26738.

[4] Albert K, Phogat KS, Anhalt F, et al., 2020, Structure-Preserving Constrained Optimal Trajectory Planning of a Wheeled Inverted Pendulum. IEEE Transactions on Robotics, 36(3): 910–923.

[5] Gawryszewski M, Kmiecik P, Granosik G, 2017, V-REP and LabVIEW in the Service of Education. Robotics in Education: Research and Practices for Robotics in STEM Education. Springer International Publishing, 2017: 15–27.

[6] Rohmer E, Singh SPN, Freese M, 2013, V-REP: A Versatile and Scalable Robot Simulation Framework. 2013 IEEE/RSJ International Conference on Intelligent Robots and Systems. IEEE, 2013: 1321–1326.

[7] Kafetzis I, Moysis L, 2017, Inverted Pendulum: A System with Innumerable Applications. School of Mathematical Sciences, 2017.

[8] Ghayoor F, 2020, A MATLAB-Based Virtual Robotics Laboratory: Demonstrated by a Two-Wheeled Inverted Pendulum. The International Journal of Electrical Engineering & Education, 57(4): 301–320.

Publisher's note

Bio-Byword Scientific Publishing remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.