



Virtual Reality Based Simulation for Linear Control Experiments

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Abstract. Owing to its good immersion and interactivity, virtual reality technology has been broadly applied in the field of education. To enhance the experimental teaching of linear control theory, a VR based virtual experiment system was designed and developed using Unity 3D and MATLAB tools. The proposed system can realize control algorithm simulation of the inverted pendulum in virtual environment to improve students' interest in learning and enhance teaching efficiency.

Keywords: Virtual Reality · Linear Control Experiments · Control Simulation

1 Introduction

With the development of global information construction, virtual environment combined with virtual reality and human-computer interaction technology came into being, which has been widely used in industrial manufacturing, military, medical and entertainment fields [1–3, 6, 7]. Due to the good immersion and interactivity of Virtual Reality (VR) technology, it has broad application prospects in the field of education and can realize virtual classrooms, virtual laboratories, and other virtual environments. Virtual experiment system is a new situation in education and teaching [8, 9]. It combines virtual reality technology, human-computer interaction technology, and traditional teaching methods. Through multimedia information such as images, text, and 3D animation, virtual experiment system fuses the real environment into the virtual environment, breaks through the limitations of time and space, and provides the possibility for students to practice at anytime and anywhere.

As a professional course of control science and engineering, the linear control theory has always emphasized the combination of theory and practice. At present, many colleges and universities are actively exploring how to better combine theory and practice teaching in the teaching process [5]. In this context, this paper develops a virtual experiment system based on Unity3D and MATLAB tools. The linear quadratic regulator (LQR) control simulation of the inverted pendulum is realized in the virtual experiment system with the help of the Kinect sensor. By making full use of the advantages of information technology, the teaching methods are innovated, and the knowledge learning is assisted by science and technology so that students are not limited by time and place for teaching experiments. At the same time, it has high security, reduces the cost of laboratory construction, and improves students' autonomous learning ability.

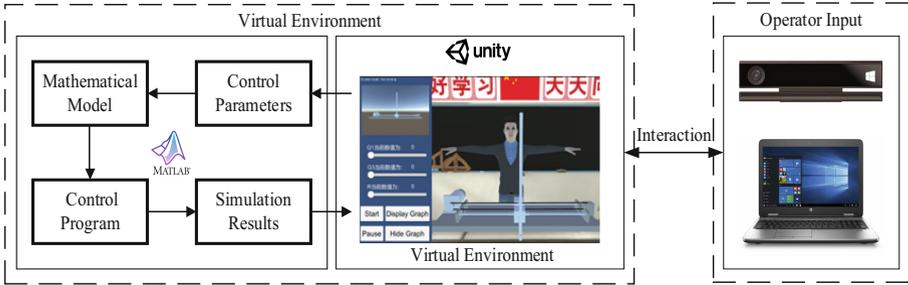


Fig. 1. Virtual experiment system architecture.

2 System Structure

This paper designs and implements the framework of virtual experiment systems. The primary equipment includes desks, chairs, lectern, blackboard, clock, triangle, and other teaching tools. This paper has carried on the three-dimensional modeling. The interactive frame diagram of the immersive environment is shown in Fig. 1. The system mainly aims to improve learning effectiveness and promote the students' understanding of the inverted pendulum system.

This paper chooses Unity3D as the development tool and sets reasonable lighting, shadow, and occlusion effects in the scene. Microsoft Visual Studio 2019 is used as the script editing tool to integrate the system process. The whole virtual learning environment includes the following parts:

- The virtual environment is developed by Unity3D and MATLAB. The Unity3D is used as the development tool of UI interface, and the MATLAB is used as the development platform of inverted pendulum experiment simulation. Through data transmission and sharing, the inverted pendulum experiment simulation in 3D virtual environment is realized.
- In this paper, Kinect is used for interactive equipment, and the interaction is completed by controlling the setting of experimental parameters.

3 Mathematical Model

The physical model of a first-order inverted pendulum balance control system [4] is shown in Fig. 2, mainly composed of the car, pendulum rod, guide rail, drive belt, pulley, and control object is composed of the car and swinging rod. The swinging rod can realize 360° free swing in the vertical plane. To make the swinging bar on the car reach the final vertical balance attitude effect through swinging, it is necessary to apply a real-time variable driving force to the car, so that the car can move under the control of the driving force to realize the swing of the swinging bar and maintain the stable control effect of the vertical balance.

The physical quantities in the above physical model include the angle θ between the swinging bar and the vertical direction and the car's moving distance x on the guide rail.

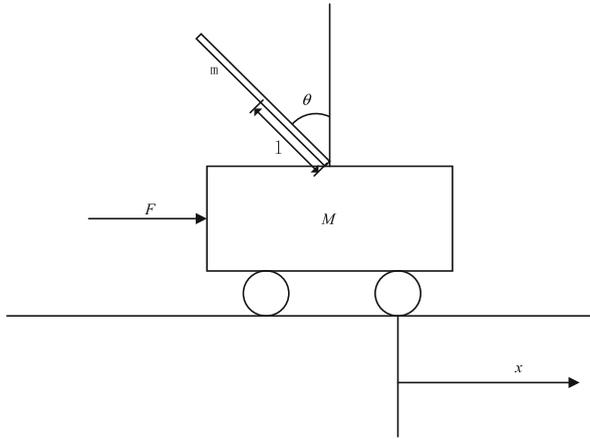


Fig. 2. The physical model of inverted pendulum.

Keeping the angle between the pendulum and the vertical direction in a small range is the prerequisite for the first-order inverted pendulum to keep the pendulum in a stable vertical state. When the pendulum can keep vertical and stable, the angle θ must be less than 5° .

Assumption: M is the quality of car, m is the quality of swinging rod; b is the car friction coefficient; l is the length of the pendulum rod axis of rotation to the rod center of mass; I is swinging rod inertia; F is the force on the car; x is the position of the car; θ is the angle of swinging rod in the vertical direction.

Neglecting the air resistance and friction and applying the Newton mechanics method, the kinematic equation of the linear first-order inverted pendulum system is derived as shown in (1) and (2).

$$(M + m)\ddot{x} + b\dot{x} + ml\ddot{\theta} \cos \theta - ml\dot{\theta}^2 \sin \theta = F \quad (1)$$

$$(I + ml^2)\ddot{\theta} + mgl \sin \theta = -ml\ddot{x} \cos \theta \quad (2)$$

After the linearization of the inverted pendulum, the differential equation is converted to a state-space equation.

$$\dot{\mathbf{x}} = \mathbf{Ax} + \mathbf{Bu} \quad (3)$$

$$\mathbf{y} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \mathbf{x} + \begin{bmatrix} 0 \\ 0 \end{bmatrix} u \quad (4)$$

Among them,

$$\mathbf{x} = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} = \begin{bmatrix} \theta \\ \dot{\theta} \\ x \\ \dot{x} \end{bmatrix} \quad (5)$$

Table 1. The values of variables.

| Name | Value | Unit |
|------|--------|------------|
| M | 1.096 | Kg |
| m | 0.109 | Kg |
| b | 0.1 | N/m |
| l | 0.25 | m |
| I | 0.0034 | Kg · m · m |

$$\dot{x} = \begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_4 \end{bmatrix} = \begin{bmatrix} \dot{\theta} \\ \ddot{\theta} \\ \dot{x} \\ \ddot{x} \end{bmatrix} \tag{6}$$

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & \frac{-(I+ml^2)b}{I(M+m)+Mml^2} & \frac{m^2gl^2}{I(M+m)+Mml^2} & 0 \\ 0 & 0 & 0 & 1 \\ 0 & \frac{-mlb}{I(M+m)+Mml^2} & \frac{mgl(M+m)}{I(M+m)+Mml^2} & 0 \end{bmatrix} \tag{7}$$

$$B = \begin{bmatrix} 0 \\ \frac{I+ml^2}{I(M+m)+Mml^2} \\ 0 \\ \frac{ml}{I(M+m)+Mml^2} \end{bmatrix} \tag{8}$$

$$u = F \tag{9}$$

The values of variables in this paper are shown in Table 1.

By substituting the values of each variable into (3) and (4), a specific state-space equation can be obtained.

$$\dot{x} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & -0.0720 & 0.0102 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & -0.0593 & 8.0837 & 0 \end{bmatrix} x + \begin{bmatrix} 0 \\ 0.7202 \\ 0 \\ 0.5934 \end{bmatrix} u \tag{10}$$

And $x, \dot{x}, \theta, \dot{\theta}$ is the position, velocity, angle and the angular velocity of the inverted pendulum. Many kinds of theoretical control algorithms can be applied to balance and stabilize the inverted pendulum, such as root locus, PID, LQR, Fuzzy logic, sliding mode,

or such new algorithms. The LQR is a typical optimal control method and can compensate for disturbances in the system and balance the inverted pendulum following the reference angle and cart position. Suppose the state equation of a given linear time-invariant system is shown in (11) and (12).

$$\dot{x} = Ax + Bu \tag{11}$$

$$y = Cx + Du \tag{12}$$

The control performance index is shown in (13).

$$J = \frac{1}{2} \int_0^{\infty} x^T Qx + u^T Ru dt \tag{13}$$

In Eq. (13), Q is a positive definite (or positive semi-definite) Hermitian or a real symmetric matrix, R is a positive definite Hermitian or a real symmetric matrix. Q and R represent the relative importance of error and energy loss respectively. The linear feedback controller is illustrated in Fig. 3.

When the system deviates from the stable state due to external interference, a certain control u^* should be applied to make the system return to the zero state and meet the minimum J . According to the optimal control theory, for the purpose of minimizing J , the optimal control obtained by the minimum principle is as follows:

$$K = R^{-1}B^T P \tag{14}$$

Then the optimally controlled variable can be obtained:

$$u^* = -R^{-1}B^T Px = -Kx \tag{15}$$

Where P is the solution of Riccati equation described as (16):

$$A^T P + PA - PBR^{-1}B^T P + Q = 0 \tag{16}$$

The feedback gain matrix K can be obtained by MATLAB command $LQR(A, B, Q, R)$. The selection of Q and R is directly related to the final result of K . $Q_{(1,1)}$ and $Q_{(3,3)}$ correspond to the angular weight of the swing bar and the position weight of the car respectively. Therefore, this paper analysed the influence of different parameters on the first-order inverted pendulum system by controlling the input size of $Q_{(1,1)}$, $Q_{(3,3)}$, and R in MATLAB. The simulation result of the LQR controller is shown in Fig. 4.

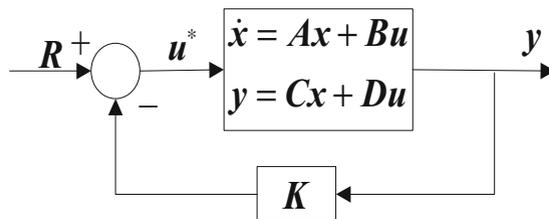


Fig. 3. Linear feedback controller.

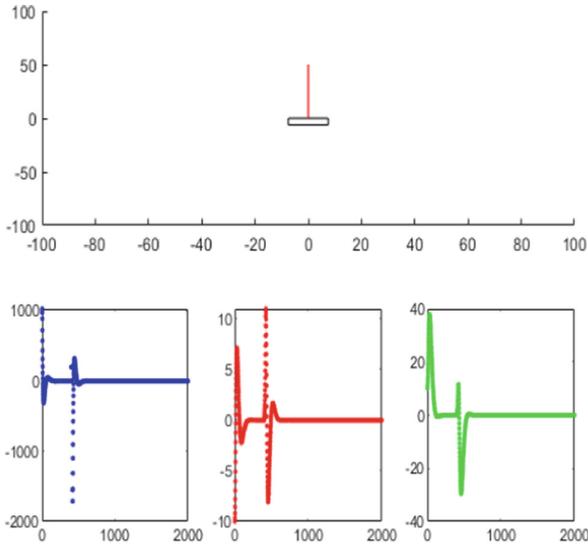


Fig. 4. Simulation results of LQR controller.

4 Realization of Simulation Interaction System

To make the virtual experiment simulation system more immersive, this paper takes Unity3D as the development platform, uses Kinect V2 sensor as an interactive input device, and realizes the input and adjustment of LQR control parameters by adding C# script and slider. The user interface of the virtual experiment system is shown in Fig. 5. At the same time, the data transmission and sharing of Unity3D and MATLAB are realized using “Shared Memory”, and the simulation results of pendulum angle and car displacement are displayed. Finally, the virtual experiment simulation of the inverted pendulum is realized.

4.1 Data Interaction

BEcause the virtual experiment system has many similarities with reality, the data of the virtual experiment system are linked with the data generated in the mathematical processing, where the variables and operating conditions that involve the inverted pendulum system are specified. The interchange of data is done in a distributed way through different partitions in “Shared Memory” because they allow to process of more information in an orderly and dynamic between the software MATLAB and Unity3D. The bidirectional interaction between the control parameters and simulation results are indicated as shown in Fig. 6. In this way, students can modify the LQR control algorithm parameters, obtain the output results of the inverted pendulum system under different parameters, learn the influence of different control parameters on the control system, and select the optimal control parameters on this basis.

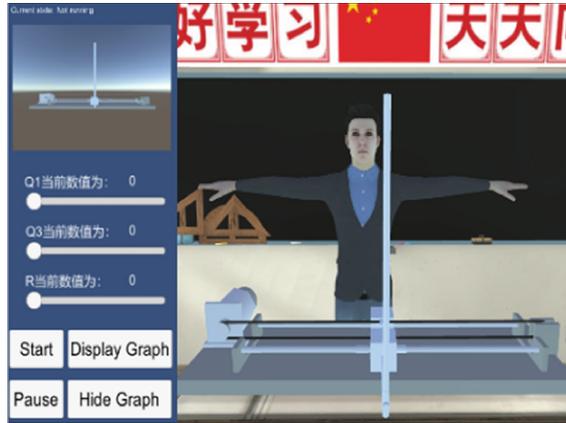


Fig. 5. The user interface of virtual experiment system.

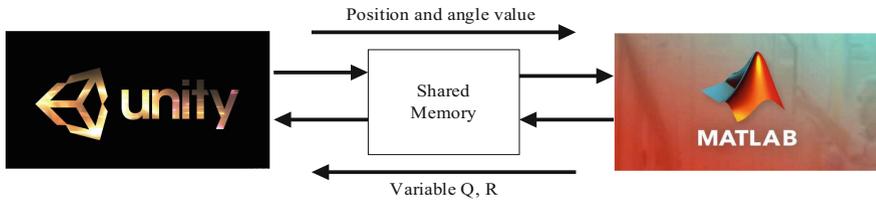


Fig. 6. Data interaction between Unity3D and MATLAB.

4.2 Realization of Virtual Experiment System

The selection of control parameters of the inverted pendulum experiment system is the top priority. The system can not only use the mouse and keyboard to input control parameters but also drive the slider in the user interface through Kinect V2 sensor as shown in Fig. 7. In this paper, the virtual avatar in virtual experiment system is controlled by Kinect V2 sensor, and the “Hand Cursor” is used to input control parameters. In addition, this paper also designs two buttons to control the operation and pause of dynamic simulation.

To better demonstrate the experimental process of inverted pendulum, this paper also designs the dynamic simulation curve of the inverted pendulum, mainly including the displacement curve of the car and the angle change curve of the pendulum rod, as shown in Fig. 8. At the same time, two buttons are also designed to display and hide the simulation curve, as shown in Fig. 9.

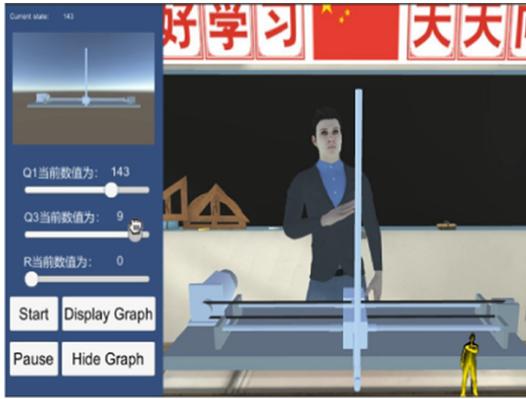


Fig. 7. Input parameters by Kinect.



Fig. 8. Inverted pendulum running state.



Fig. 9. Dynamic simulation curve.

5 Conclusions

Virtual experiment systems can use virtual technology to simulate the scene, and then assemble a complete experimental system according to the experimental requirements. This paper uses the Unity3D virtual interactive platform to develop an inverted pendulum virtual experiment system. By using C# as the main development language, the 3d inverted pendulum experimental environment was built and Kinect sensor was used to control the input of control parameters. The dynamic simulation results under LQR control algorithm were obtained and displayed in Unity3D.

This teaching way, which focuses on the combination of theory and practice, helps to improve students' subjective initiative, simulate students' interest in learning, and improve students' learning effect. With the development and popularization of virtual reality technology, virtual reality technology will give full play to its potential in the field of virtual teaching, provide students with a situational interactive experience, and help students explore the abstract and complex ocean of knowledge.

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