Second-order Self-balancing Inverted Pendulum

Ziyue Xiao*, Zhencheng Chang, Mingxuan Li, Yumei Huang
Tianjin University of Science and Technology, Tianjin, China

*E-mail: *1418249500@qq.com*

Abstract

The team utilizes the second-order inverted pendulum cart based on LQR controller for steady pendulum control with light rods. First, the second-order inverted pendulum is used as a research object to obtain its set of dynamical equations, then, the set of dynamical equations is written in the form of state-space expressions, and finally, the second-order inverted pendulum system of a balanced trolley with a light rod is controlled by a stabilized pendulum using the LQR controller. The inverted pendulum is a typical nonlinear, underdriven and unstable system, which can realize the all-round wind resistance of the rod and occupy less space with high stability.

Keywords：LQR controller，Second-order handstand pendulum，Lagrangian mechanics.

1. Introduction

In real life, many structural systems need to be stable in a variety of environments, such as high-rise buildings, bridges, tower structures, etc. One of the important factors is the influence of climatic conditions, especially wind on the building structure. Due to the uncertainty and variability of wind forces, buildings and structural systems need to be designed to be stable enough to resist the effects of wind. In practical application, in order to ensure the stability of the structural system, it is usually necessary to take various resistance measures, such as adding dampers, support devices and traction devices to the structural system, This is shown in Fig. 1.

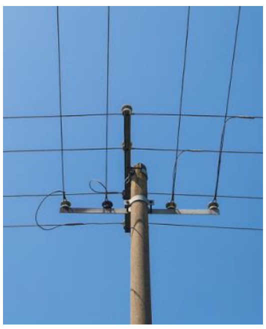


Fig. 1. Telephone poles in kind

For slender structures such as rods, due to their special morphological and material properties, the study of their stability under wind force is more complex and critical. Therefore, in order to ensure the wind resistance and stability of the rod, it is necessary to carry out relevant research and application.

To this end, it is possible to study the dynamic characteristics of the rod under the action of wind, etc., the morphological and material characteristics of the rod, and the structural design of the rod to explore how to achieve the stability of the rod. At the same time, some practical application devices can also be developed to help the rod stabilize under the action of wind and other forces, such as adding support, traction and adjustment devices [1].

However, these methods are too traditional and require the support of manpower and material resources, and when the device is damaged, it is not easy to repair, time-consuming and labor-intensive. Therefore, it is urgent to develop a new type of stable and non-falling rod device.

In view of the above shortcomings, our group proposed a second-order inverted pendulum system based on LQR controller to stabilize the pendulum control of the light bar. Our team first took the second-order inverted pendulum system of the balance trolley with light bar as the research object, analyzed its dynamics based on the Lagrangian mechanics method, obtained its dynamic equations, and then wrote the dynamic equations into the form of state space expressions, and finally, after a brief overview of the LQR controller, the LQR controller was used to stabilize the second-order inverted pendulum system of the balance trolley with light bar. The inverted pendulum is a typical nonlinear, underdriven, and unstable system. Through the research and optimization of the inverted pendulum system, our team has obtained new control algorithms, which have application prospects in robot control, missile interception control, aviation docking control and general industry.

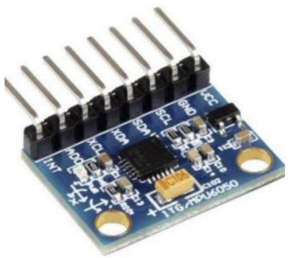
2. Hardware Usage Programme

2.1 Mpu6050

MPU6050 is a commonly used six-axis inertial measurement unit (IMU) consisting of a gyroscope and an accelerometer. It is capable of measuring changes in the rotation and acceleration of an object in three axes.

MPU6050 has a built-in 3-axis gyroscope and a 3-axis accelerometer that can communicate with the microcontroller via an I2C or SPI interface. It is widely used in robots, drones, game controllers, and other applications that require gesture perception or motion tracking [2].

With MPU6050, you can obtain the angular velocity and acceleration data of an object, which can be used to calculate the object's pose or perform motion tracking. This is shown in Fig. 2,



Fig, 2 MPU6050

2.2 STM32C8T6

STM32C8T6 is a 32-bit ARM Cortex-M3 core microcontroller from STMicroelectronics. It has high performance, low power consumption, a wide range of peripheral interfaces and rich development resources, and is one of the commonly used MCUs in embedded system development.

STM32C8T6 has expandable memory and peripheral interfaces, including high-speed USB, CAN bus, multiple serial communication interfaces, analog-to-digital converters and digital-to-analog converters, etc., and has a wide range of applications in industrial control, automotive electronics, home appliance control, medical equipment, smart home and other fields.

In addition, STM32C8T6 has a wealth of development resources, including development boards, online IDE tools, official documentation, and community support, which facilitate engineers to quickly develop and test embedded system applications.

3. System programming

3.1LQR control

After the above qualitative description of the LQR controller, the simulation calculation was carried out by the relevant functions of Matlab (the mass of the body is 0.9 kg, the height is 0.126 m, the mass of the rod is 0.1 kg, and the length is 0.390 m [3], which is shown in Fig. 3.

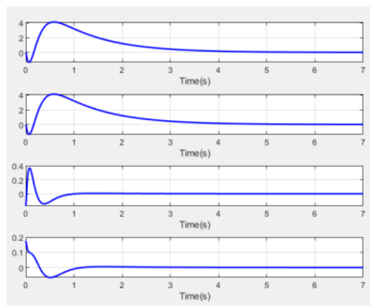


Fig. 3 MATLAB simulation results

The device was then simulated with Simulink, and the results are shown in Fig. 4.

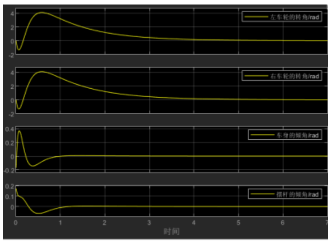


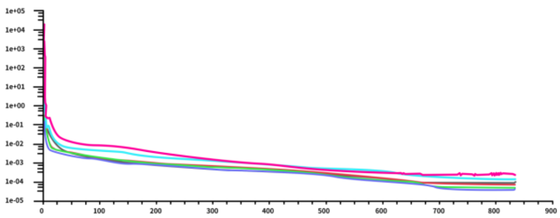
Fig. 4 Simulink simulation results

It can be seen from Fig. 2 that under the action of wind, the rotation angle of the wheel of the second-order inverted pendulum system with light rod reaches the maximum at 0.7s, and the rotation angle of the wheel reaches the maximum at 0.05s, and the second-order inverted pendulum system with light rod gradually tends to stabilize at 2s and basically achieves the stable effect at 3s [4].

3.2Wind simulation

Wind Simulation We use Fluid Dynamics (CFD) simulation, which is a method of simulating fluid flow and force on objects through numerical calculations. When simulating the action of wind, the flow of the wind field can be simulated by establishing a mathematical horizontal shape, and the object to be tested can be added to the horizontal simulation, and the wind force on the object can be calculated through numerical calculation.

We perform a CFD simulation of a second-order inverted pendulum model with a light bar, and the results are shown in Fig. 5.



Fig, 5 CFD simulation

Wind power is the key to test the stability of the second-order inverted pendulum trolley with light bar, and the control variable method is used to test the wind power of the second-order inverted pendulum trolley with light bar. In physics, the method of controlling factors is often used to control multi-factor problems, turning multi-factor problems into multi-factor problems. Only one of the factors is changed at a time, and the remaining factors are controlled unchanged, so as to study the influence of the changed factor on things, study them separately, and finally solve them comprehensively, this method is called the control variable method. It is an important method of thought in scientific inquiry, and is widely used in various scientific explorations and scientific experiments.

4. Introduction of Functional Module

4.1Simulink emulation

For the test of the second-order inverted pendulum, a combination of simulation and reality is used. First, the system was simulated using Simulink to obtain the state data of the device. It is then combined with the real thing to verify the correctness of the simulation data. The controllable FS-75 industrial fan was used to perform wind tests on the second-order inverted pendulum system with light rods, and the device data was measured by changing the length, weight, and material of the rods. Through continuous simulation and testing, the efficiency of simulation testing is improved and the trial and error time is reduced. Extensive testing to ensure the correctness of the simulation and the ability to improve the simulated model in real time complement each other for continuous improvement.

4.2 FS-75 Industrial Fan Test

Experiments with a controllable FS-75 industrial fan and anemometer allow for better control of single variables for experimental measurements. After the experimental model is established, the system can be simulated and measured by Simulink rods of different lengths, weights, and materials, which greatly reduces the experimental time and improves the accuracy of the experimental data, which is shown in Fig. 6.

Fig. 6 FS-75

5. Synthesis

In this experiment, the second-order inverted pendulum system was used to carry out the non-inverted experiment on the light rod, and the second-order inverted pendulum system with light rod was simulated by Simulink, and the system gradually stabilized in 2s. Then, the second-order inverted pendulum system with different rod lengths, different system states and different materials was simulated respectively, and the data state of the optimal second-order inverted pendulum system and device with light rod was obtained, and the influence of using different controllers on the stability of the device was discussed, and the time error was calculated to obtain the best controller. Then, combined with the real thing, the wind test of the second-order inverted pendulum system with light rod was carried out with the controllable FS-75 industrial fan and the stability test of the device was carried out by changing the length of the light rod, and it can be concluded that the experimental device has high stability, and the time to reach the stable state at the wind speed of 1 ~ 3m/s is 0.72s, 0.91s and 1.33s respectively, and the length of the rod is increased within a certain range, and the system can achieve stability, which meets the requirements of physical experiments [5].

In this experimental setup, the second-order inverted pendulum handstand model was studied, the optimal handstand state was discussed under different rod lengths and materials, the stability of the system was simulated under different external disturbances (wind speeds), and the influence of different controllers on the stability of the device and the time error were discussed. In the future, it is planned to change the length of the trolley (lower rod part) in the experimental device and simulate the measurement. Multiple fans were used to test the device to discuss whether the device could be more stable in more complex situations.

6. References

[1]. Hui-Hui Zhang, B.J. Hou, J. Gao, et, al, Research and implementation of stable pendulum control for linear inverted pendulum based on LQR, *Mechanical Design and Manufacturing*, 2023.7, pp. 1-6

[2]. Jiang, Lingyun,Xu, Bingji,Zhang, Fenghua, et, al, A study on a stabilisation control algorithm for linear two-stage inverted pendulums, *Computer Simulation*, 2023.Vol. 40, pp. 314-320

[3]. Hui-Wen Shi, Jie Zheng, MATLAB and ADAMS simulation study of linear inverted pendulum based on model predictive control, *Industrial Technology and Vocational Education*, 2023 XXI, pp. 1-5

[4]. Liu, Jiawei, Song, Nan, et, al, Optimisation and real-time simulation of inverted pendulum control system, *Chemical Automation and Instrumentation*, Vol. 50, 2023, pp. 453-458

[5]. Ji Hong, Wang Yingli, Zhao Zhongyi, et, al, Mathematical modelling and system performance analysis based on a two-stage inverted pendulum, Mechanical Design, *Vol.* 2023, No. 40, pp. 137-142

Authors Introduction

Mr. Ziyue Xiao

He is hold a positive and serious attitude towards work, have a strong sense of responsibility, be sincere, meticulous, optimistic, and stable, and can continuously learn and improve oneself in practical wor

Mr. Zhencheng Chang

He is currently pursuing his undergraduate degree at the School of Electronic Information and Automation, Tianjin University of Science and Technology.

Ms. Mingxuan Li

Her major is environmental science. She is currently a undergra student in Tianjin University of Science and Technology.

Ms. Yumei Huang

She studied at Tianjin University of Science and Technology in 2021. She is now the first major in her faculty and is expected to receive her Bachelor's degree in 2025.