Simulation Modelling Practice and Theory 81 (2018) 31–50

Contents lists available at ScienceDirect

Simulation Modelling Practice and Theory

journal homepage: www.elsevier.com/locate/simpat

Linear motor driven double inverted pendulum: A novel mechanical design as a testbed for control algorithms

Xianmin Chen[a,1,2], Rongrong Yu[b,1,2], Kang Huang[b], Shengchao Zhen[b,*], Hao Sun[b], Ke Shao[b]

[a] *University of Science and Technology of China, Hefei, Anhui 230027, PR China*
[b] *School of Mechanical Engineering, Hefei University of Technology, Hefei, Anhui 230009, PR China*

A R T I C L E I N F O

Article history:
Received 17 July 2016
Revised 22 November 2017
Accepted 30 November 2017

Keywords:
Double inverted pendulum
Linear motor
LQR controller
Cspace
Control algorithm testbed

A B S T R A C T

The inverted pendulum is a classic experimental facility that is widely used as a benchmark for testing control algorithms. One of the difficulties, however, with the traditional inverted pendulum is that it is not a very challenging problem to compare modern control techniques. In addition, it is usually driven by a rotary motor and transmission system that introduces mechanical friction forces as well as periodic and aperiodic disturbances which result in the pendulum performance not as repeatable as desired. In particular, this lack of repeatability, which is very difficult to model, makes the use of this traditional control testbed less desirable for developing and comparing various modern control techniques. Therefore, it is the purpose of this paper to describe a more repeatable but more complicated inverted pendulum system as a benchmark system for testing control strategies. The proposed system includes the use of a linear drive motor to eliminate the difficulties associated with the rotary transmission. In addition, a second inverted pendulum is added to create a richer control space and thus be a more effective benchmark for controller evaluation.

1. Introduction

The inverted pendulum system is one of the classic mechanical systems in control systems that has attracted a great deal of attention from researchers and robotics enthusiasts in the last few decades due to its special features, such as high order, instability, multivariable, nonlinearity, strong coupling and under-actuation [1]. Besides, it can effectively reflect a lot of the key performance of the control algorithm, such as robustness, stabilization and traceability [2–4]. The inverted pendulum system is a classic example to research control algorithms in the control field [5], for the performance of the system can be reflected by the angle of the pendulum and the displacement of the cart directly. Therefore, the inverted pendulum system is widely used to test and compare the features between them [6]. The control technology of inverted pendulum can applied in many industrial and engineering products such as high-precision control of the robot posture [7], one or two wheeled self-balancing vehicle control [8,9], stabilization control of launching rocket and attitude control of satellite, etc.

* Corresponding author.
E-mail addresses: rongala91@163.com (R. Yu), zhenshengchao@qq.com (S. Zhen).
[1] These two authors contributed equally to this work and should be considered co-first authors.
[2] The George W. Woodruff School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA, 30332, USA.

https://doi.org/10.1016/j.simpat.2017.11.009
1569-190X/© 2017 Published by Elsevier B.V.

In general, the control of inverted pendulum system by classical methods is difficult. This is mainly because the cart-inverted pendulum is an under-actuated nonlinear system, with only one control input applied to the cart but more than two outputs (cart position and pendulum angle) [10]. In 1966, Schaefer and Canon stabilized a crankshaft to an inverted position based on the Bang-Bang control theory. Subsequently, the concept of the inverted pendulum is proposed. In 1969, Lindorff [11] successfully controlled the single inverted pendulum system. In 1972, Sturgeon and Loscutoff [12] achieved the control of double inverted pendulum. Furuta completed the attitude control of a triple inverted pendulum successfully in 1984 [13]. Li [14] achieved stable control of quadruple inverted pendulum in 2002. In 2014, Weaver et al. [15] determined the degree of inverted pendulum model which is suitable for stooping and crouching postures control.

There are also many control algorithms applied to the multi-stage inverted pendulum, such as PID control [16], fuzzy control [17,18], LQR control [19], sliding control [20–23], neural network control [24], adaptive control [25], fault-tolerance control [26], et al, and even the combination of control algorithms [27,28]. But all these proposed novel control algorithms need a repeatable testbed to verify its effectiveness.

Therefore, many different experimental platforms are designed by researchers to verify the reliable of control algorithms. Furuta et al. [29] used microcomputer to control double inverted pendulum, and then they realized the control of a double inverted pendulum on an inclined guide rail in 1978. Wakuya et al. [30] constructed an on-line training model for self-turning control algorithm whose effectiveness was investigated through control an inverted pendulum in 2007. Chee et al. [31] designed a robust sensor fault reconstruction applied in an inverted pendulum to test real-time results. Cong et al. [32] compared the actual real-time experiment control results of the single inverted pendulum system with the pole-placement method, the optimization strategies of LQR and the LQY methods. Many control algorithms of inverted pendulum are based on the linearization model of the inverted pendulum as in reference [33–35]. Xu et al. [36] submitted a fuzzy control algorithm based on variable structure, and have successfully finished the stability control.

However, the cart of the above-mentioned inverted pendulum systems is driven by a rotary motor and by mechanical transmission components to keep the balance of the inverted pendulum [37]. With this kind of configuration, the transmission frictions as well as the periodic and aperiodic disturbances are included in the system. Especially, most of the traditional inverted pendulums use belt conveyor for linear motion while the conveyor belt will produce vibration, extension, and delay. All the disturbing signals are inevitable for the system. The presence of these will lead to the lack of repeatability, which is very difficult to model, makes the use of this traditional control testbed less desirable for developing and comparing various modern control techniques. Up to now, how to implement the real-time control of an inverted pendulum is still very difficult, so decrease the disturbing signals is beneficial for the real-time control of the inverted pendulum.

To exploit a more accurate and repeatable experimental platform with less disturbing signals (such as transmission friction, interval, thrust fluctuation, periodic and aperiodic disturbances for control theory research) for testing and evaluating control algorithms of the inverted pendulum system, an innovative linear motor driven double inverted pendulum (LMD-DIP) system is designed. To avoid long time programming and debugging, Cspace which is based on the TMS320F2812DSP control card and MATLAB/Simulink is designed to realize the real-time control of the system. Chen and Cao [38–40] used linear motor on the design of inverted pendulum, and expressed the characteristics are superior to rotary motors. But these references lack of systemic. In this paper, the hardware and software platform we designed is not only applicable to the double inverted pendulum, but also can verify the repeatable of the testbed by different control algorithms.

This paper aims to describe a more repeatable but more complicated inverted pendulum system as a benchmark system for testing control strategies, which include hardware platform and software platform. This paper is organized as follows. Section 2 describes the hardware platform design, including the novel LMDDIP system and the design of the hardware control platform. Section 3 presents the software platform design (Cspace, rapid controller prototyping system) of the system in detail. Section 4 is the application of the platform. In this section, we first derive the mathematical model and the state equation of the designed system (more details of the derivations are given in Appendix). Second, experimental tests by using LQR and sliding mode control algorithms are carried out respectively. And during the LQR control algorithm, we also simulate the system by MATLAB. Finally, there is some summary in Section 5.

2. Hardware platform design

2.1. Linear motor driven double inverted pendulum

The traditional straight-line motion is driven by rotary motor and transmitted by using ball or roller screws or belts and pulley general. The problem of these structures is that the mechanical friction forces as well as periodic and aperiodic disturbances which result in pendulum performance not as repeatable as desired. It is also hard to get high precision, high speed and fast response based on these systems. While linear motor is a device that converts electric energy to mechanical energy of linear movement directly. This way of driving with a linear motor is called “direct drive” or “gapless drive” . It is often simply described as a rotary motor that has been rolled out flat, and the principles of operation are the same. It has the distinct advantages over traditional mechanical systems with high speed, high acceleration and high accuracy, but without mechanical friction. What’s more, its maximum stroke is unlimited. Most of the linear motors are linear induction motors or linear synchronous motors. In this paper, an ironless permanent magnet linear synchronous motor is used to drive the double inverted pendulum. Features of the linear motor are as follows (Table 1).