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Araştırma Makalesi / Research Article

PID Control of an Inverted Pendulum with Experimental Friction Model Estimation

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Keywords

Inverted Pendulum; PID; Duty Cycle; Digital Signal Processor; Stability

Abstract

An inverted pendulum system is designed, implemented, and stabilized on a short path. Proportional-Integral-Differential (PID) control algorithm is embedded on a digital signal processing card to achieve the stabilization in a real time. DC-motor dynamics of the inverted pendulum system and cart-track friction are unknown and their effects are taken into account by the incremental duty cycle approach. Experimental tests, conducted for various experimental conditions, have shown that the inverted pendulum system reached the desired state in the presence of friction and various external disturbances.

Deneysel Sürtünme Modeli Kestirimiyle bir Ters Sarkacın PID Kontrolü

Anahtar kelimeler

Ters Sarkaç; PID; Serbest Çevrim; Sayısal İşaret İşleme; Kararlılık

Öz

Bu çalışmada, kısa bir hat üzerinde ters sarkaç sistemi tasarlanıp, uygulanmış ve kararlı bir şekilde kontrol edilmiştir. Kararlılığı sağlamak için gerçek zamanlı sayısal bir işaret işleme kartına Oransal-İntegral-Diferansiyel (PID) kontrol algoritması yerleştirilmiştir. Ters sarkaç sisteminin DC motor dinamiği ve araç yolu sürtünmesi bilinmemektedir ve sürtünme etkileri arttırılan serbest çevrim yaklaşımı ile dikkate alınmıştır. Sürtünme ve dış gürültü varlığında farklı deney koşulları için yapılan testler ters sarkacın istenen denge durumuna ulaştığını göstermiştir.

1. Introduction

The inverted pendulum problem is one of the benchmark problems in dynamics and has been studied extensively in the control literature. In this work, an inverted pendulum and its control system have been designed, implemented, and tested. The inverted pendulum system has a single input, which is the force created by the DC motor voltage, and two outputs, which are the angle of the pendulum and position of the cart. In the literature numerous control algorithms are applied to the inverted pendulum systems, and many satisfactory results are reported. In the inverted pendulum systems, the pendulum is attached to the cart via hinge. The cart is designed to move only in the forward and backward directions on the sliding path. The cart motion affects the motion of the pendulum so that the pendulum moves either in the clockwise direction or in the counterclockwise direction, depending on the cart's motion. The control objective for the inverted pendulum system is to move the cart to a pre-specified position while keeping the pendulum balanced. This problem is called the inverted pendulum stabilization problem. In this work the control objective is achieved under the PID control in the presence of frictions and external disturbances. Some significant studies, in which inverted pendulum systems are addressed, are summarized next. In (El-Hawwary *et al*. 2006), an experimental setup is described and stability of the system is achieved under the adaptive fuzzy control. Intelligent control methods including fuzzy logic and neural network methods have been used for inverted pendulum systems in (Hung *et al*. 1997,Magana *et al*. 1998). A more challenging inverted pendulum problem, a double inverted pendulum problem, is studied in (Cheng *et al.* 1996). In another work, the mobile inverted pendulum is developed and tested by using an intelligent co1079ntrol algorithm (Jung and Kim 2008, Tao *et al*. 2008) are suggested the inverted pendulum and cart system is effectively approximated by a Takagi–Sugeno (T-S) fuzzy model in a small range of angle near its equilibrium state . An adaptive state controller was developed for a stable, and in the same time optimal balancing of an inverted pendulum and a switching mechanism between swinging and balancing algorithm is proposed by (Muskinja and Tovornik 2006). The basic proportional-integral-derivative (PID) control algorithms are implemented in an FPGA chip and a neural network controller is implemented in a DSP board by (Jung and Kim 2007, Gani et al. (2014) took a fuzzy logic based approach for controlling the inverted pendulum. Finally in (Kharola et al. 2016), aimed to stabilize an inverted pendulum system on a sloping surface using PID and fuzzy logic controllers. A very common use of the inverted pendulum systems is for the educational purposes to illustrate validity of various algorithms. In this study, cart position and pendulum angle data are supplied to the PID controller to generate control signals for balancing the inverted pendulum. The control signal takes the unmodeled system dynamics, including the static and dynamic frictions, into account. In particular, overcoming the static friction is based on increasing the PWM duty cycle of the voltage applied to the DC motor. That is, at certain duty cycle, the average voltage value corresponding to the minimum voltage that overcomes the static friction is obtained. After overcoming the static friction, the dynamic friction becomes effective in the motion of the cart. In this phase of the motion the PID controller embedded in the DSP card takes over the control.

2. Overall System Description

The mechanical description and block diagram of the inverted pendulum system designed and implemented are shown in Figures 1 and 2 respectively. The pendulum is hinged to the cart in a way that it can move only in the clockwise and counterclockwise directions in the *x-y* plane. Direction of the pendulum motion is controlled by adjusting the DC motor voltage that generates the force applied to the cart. The cart is mounted on a DC motor with belt. Position of the cart and angular position of the pendulum are measured by two incremental encoders mounted on the motor and pendulum respectively.

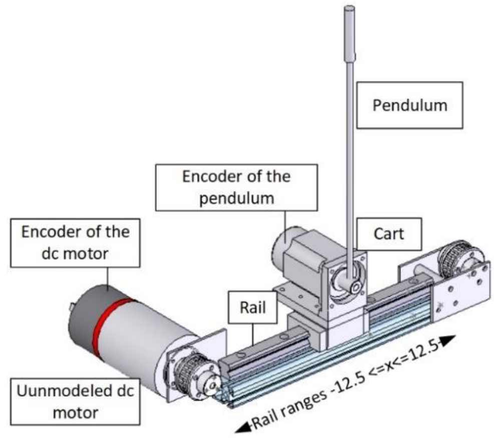

Figure 1. Mechanical description of the inverted pendulum (Gün,A. 2007)

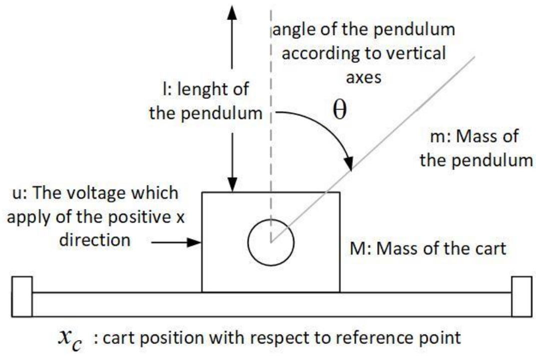

Figure 2. Block diagram representation of the Inverted pendulum system (Int Kyn. 3)

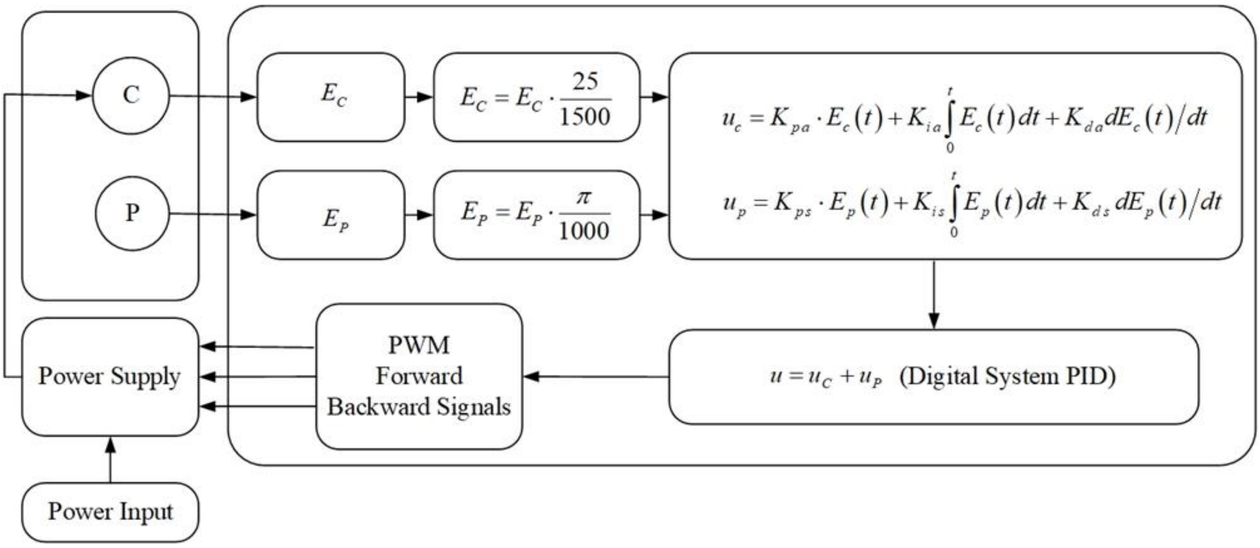

Figure 3. PID control block diagram (Wang, 2011)

3. PID Control

PID control is a classical control algorithm used extensively in many control applications. The block diagram representation of the PID controller for the inverted pendulum system is shown in Figure 3. In the diagram E_C and E_P represent the error signals for the cart position and the pendulum angle. They are defined by

$$E_p = \theta_d - \theta \quad (1)$$

and

$$E_c = x_d - x_c \quad (2)$$

where θ_d and θ are the desired and actual angles of the pendulum, and x_d and x_c are the desired and the actual positions of the cart respectively. Using the error signals, intermediate PID control inputs are computed by

$$u_p = K_{pp} \cdot E_p(t) + K_{ip} \cdot \int_0^t E_p(t)dt + K_{dp} \frac{dE_p(t)}{dt} \quad (3)$$

and

$$u_c = K_{pc} \cdot E_c(t) + K_{ic} \cdot \int_0^t E_c(t)dt + K_{dc} \frac{dE_c(t)}{dt} \quad (4)$$

where K_{pp}, K_{ip}, K_{dp} , K_{pc}, K_{ic} and K_{dc} are the PID gains. The PID control input for the overall system is the sum of u_p and u_c.

$$u = u_c + u_p \quad (5)$$

The value of *u* is used to calculate the duty cycle of the PWM signal applied to the cart. It will, in the sequel, be presented that the duty cycle is proportional to the *u* value.

4. Hardware Implementation

In this work, TI TMS320F2812DSP DSP electronics card is used as the controller hardware and PID algorithm is embedded in this card. The hardware diagram of the overall system is shown in Figure 4. The controller TMS320F2812DSP generates PWM signals for the DC motor drivers and receives signals from encoders. Signals received from encoders are processed to determine the pendulum angle and cart position. The actual picture of the hardware implementation is shown in Figure 5 .

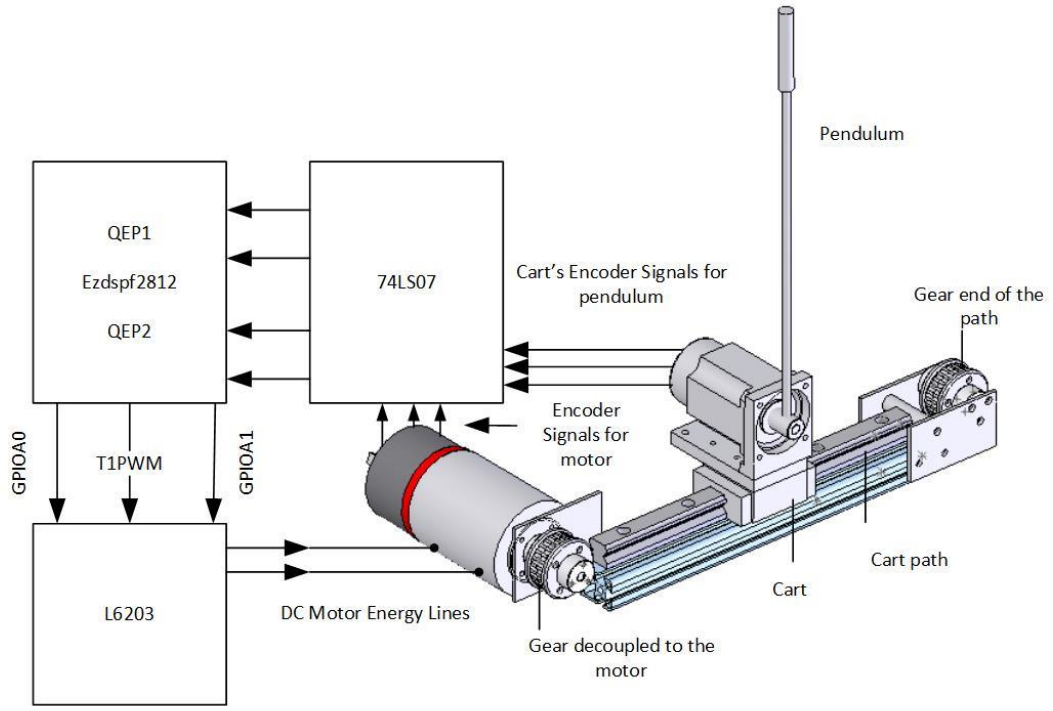

Figure 4. Inverted pendulum hardware diagram(Gün, A. 2007)

This system has two encoders. The one for the pendulum produces 1000 pulses per revolution; and the one for the motor produces 2000 pulses per revolution. The length of the cart movement range is 25 cm, which can be viewed as ± 12.5 cm from the center of the track. This is a challengingly short track length (Asa*etal*.2008). The inverted pendulum and the cart are required to reach their desired states and keep these states thereafter. The numbers stored at u_p and u_c can be interpreted as the angles in radians and distance from the center of track in centimeters by considering formulas for their ranges.

$$\theta \in \left(-N_p \cdot \frac{\pi}{1000} rad, \quad N_p \cdot \frac{\pi}{1000} rad \right)$$

and

$$x \in \left(-N_c \cdot \frac{12.5}{750} cm, \quad N_c \cdot \frac{12.5}{750} cm \right)$$

where N_p and N_c are encoder outputs for pendulum and cart respectively. The pendulum and cart direction information are sent to Ezdspf2812 DSP board through 74LS07 buffer which are reading from encoders. The block diagram of the mechanism of encoders is shown in Figure 6.

Figure 5. Hardware implementation of the inverted pendulum (Gün,A. 2007)

5. DC Motor Driver Circuit

L6203 DMOS full bridge driver circuit is used as the DC motor driver. Figure 7 shows the circuit layout of this driver which has the feature that prevents theinstant voltage variations in fast switching application. The direction information of the motor is fed to IN1 and IN2 digital inputs. The L6203 driver consists of power transistors which are capable of carrying maximum 5 Amps.

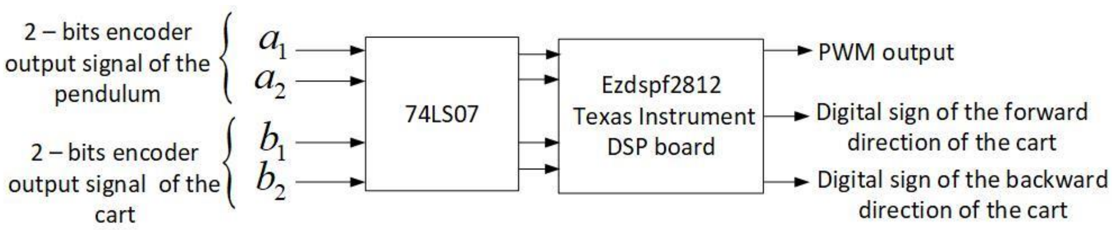

Figure 6. The block diagram of the encoder mechanism(Int Kyn. 2)

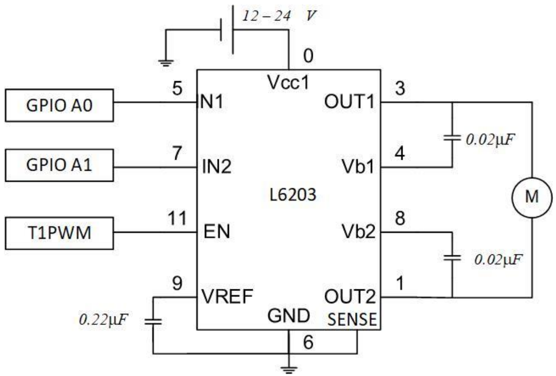

Figure 7. The circuit layout to prevent instant voltage variations in fast switching applications

(Int Kyn. 1)

6. Experiments

The practical inverted pendulum system is designed and setup on the sliding rail as shown in Figure 8. The DC motor voltage and duty cycle limits should be defined to overcome the frictional losses, which are essential to carry out duty cycle tests. Andrew (2005) development of a speed control system using matlab and simulink, implemented with a digital signal processor, M.S. thesis, Dept.Electr. Comput. Eng., Central Florida Univ., Orlando,Florida, USA. Duty cycle tests are illustrated in Figure 9. The highest PWM signal period which is embedded into TMS320F2812DSP with program is adjusted to 20 kHz for inverted pendulum system and tested for different duty cycles to move the cart. Duty cycle and average voltage are calculated with the following equations:

$$a = \frac{P}{T} \tag{6}$$

where *P* is the register content corresponding to the logical one level applied to the L6203 power circuit, *T* is the register content corresponding to the period of the PWM signal, and a is the duty cycle ratio. The complete period in the system corresponds to the register value 7500. Duty cycle ratio is experimentally found approximately 63% to accelerate motor under the static frictions. Figure 9 also illustrates lower duty cycles which couldn't overcome the static friction. The equation below yields average DC motor input voltage:

$$v(t) = a(t) \cdot V_0 \tag{7}$$

where V_0 is constant voltage which the power circuit outputs when the duty cycle is at one level. The PID constants of the control system are tuned to their right values by the trial and error method. To determine the performance of the inverted pendulum system two experiments will be conducted. In both experiments, the initial pendulum angle is selected as zero. The inverted pendulum variables and their values are given in Table 1. The first experiment is designed to illustrate consequences of utilizing the PID control algorithm alone. The experiment starts upon a disturbance applied to the pendulum by hand.

Table 1. Experimental variables and their values

Experimental variables	Value	Unit
DC motor voltage(maximum)	15	Volt
Mass of the cart	1	kg
Mass of the pendulum	0.1	kg
Initial position of the pendulum (vertical)	0	Radian
Length of the pendulum	35	cm
Length of the path	25	cm
Initial position of the cart (horizontal)	0 (midway of the rail)	cm

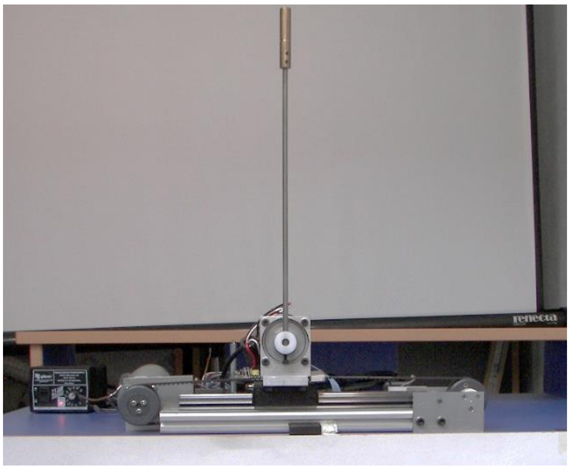

Figure 8. The Inverted pendulum designed on the sliding rail (Gün,A. 2007)

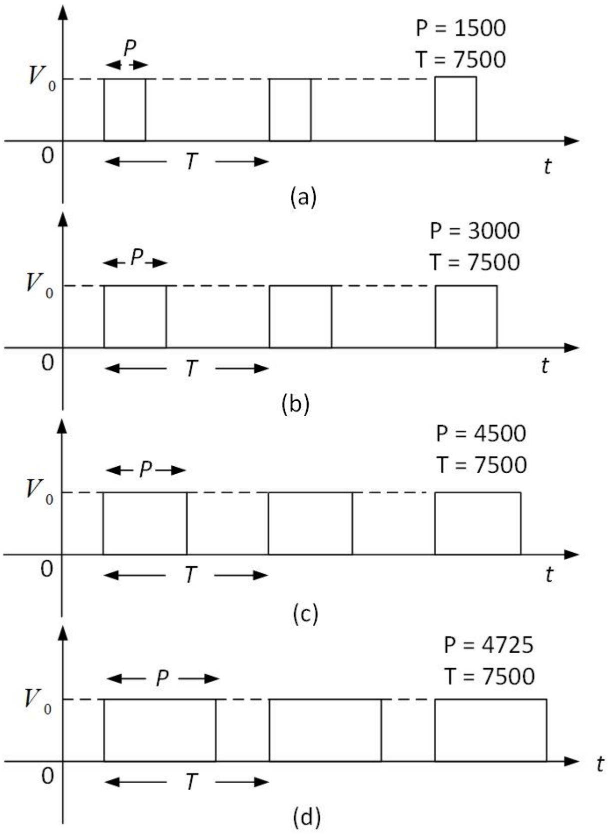

Figure 9. The DC Motor duty cycle tests graphs; in (a), (b), and (c) the DC motor cannot overcome the static friction; in (d) the minimum duty cycle so that the motor overcomes the static frictions

The system was in rest until the PID program in Ezdspf2812 was executed. In this experiment, there is no use of pendulum angle apart from inputting it to the PID controller. Immediately after the excitation of the pendulum by hand (small strike to the pendulum), the change of the pendulum angle produces an error. This error drives the PID algorithm described by Equations (1 - 5). Using the output of this algorithm the PWM signal is determined. If PWM signal is positive, IN1 input of the DC motor driver should be active and other input should be passive, in the opposite case (i.e. when the PWM signal is negative), then IN2 input of the DC motor driver should be active and other input should be passive as shown in Figure 7. In this experiment, it has been observed that the cart oscillates between x_1 = -7 cm and x_1 = +7 cm, and the pendulum angle varies in between x_3= - 0.02 radian and x_3 = + 0.02 radian. The oscillations are due the friction effects which we will eliminate in the secondexperiment. The experimental results are shown in Figures 10-12.

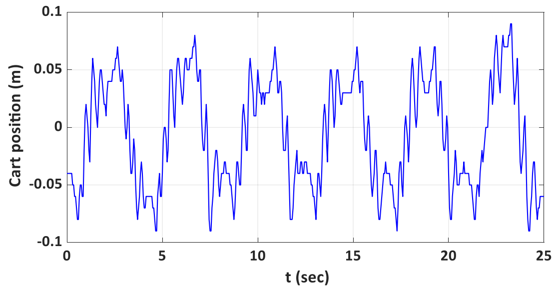

Figure 10. Time response of the cart position

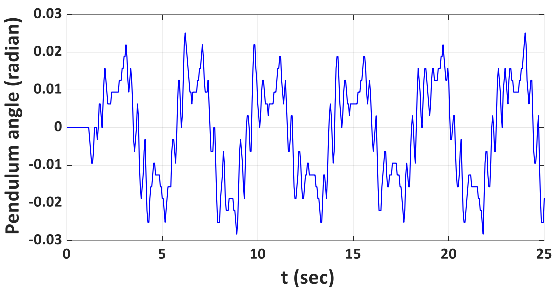

Figure 11. Time response of the pendulum angle

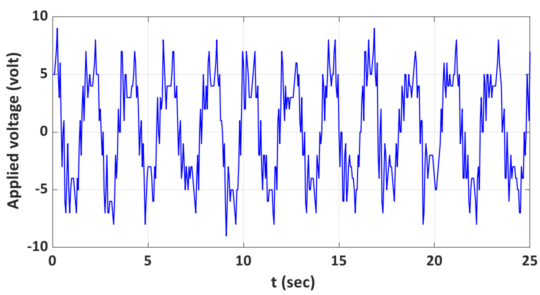

Figure 12. Time response of the applied voltage

In the second experiment it is aimed to eliminate the oscillations. It also starts with applying a small disturbance to the pendulum by hand. Besides the PID algorithm, upon detecting the cart position and pendulum angle in a very close neighborhood of the desired state, the motor input is set to zero volt. This may be called the small angle approach along with the PID control. As a result, the system oscillates about 3 seconds before reaching the equilibrium state. The cart position, pendulum angle and applied motor voltage versus time are shown in Figures 13-15 respectively.

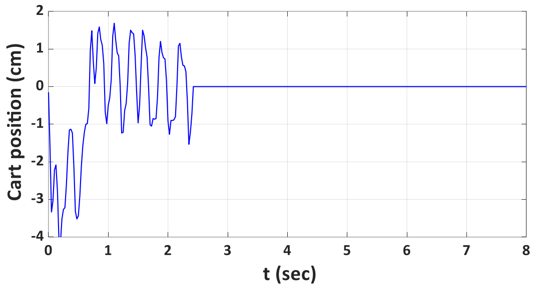

Figure13. Time response of the cart position in Experiment 2

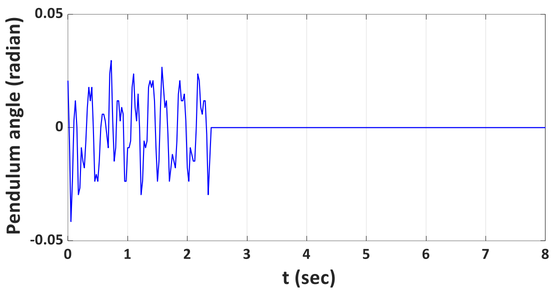

Figure 14. Time response of the pendulum angle in Experiment 2

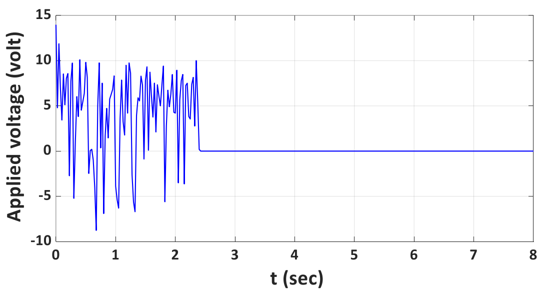

Figure15. Motor voltage versus time in Experiment 2

7. Conclusion

In this study, an experimental implementation of an inverted pendulum control system is presented. Inverted pendulum angle and cart position are measured using encoders. By means of these encoders PID controllers are driven to stabilize the inverted pendulum system. It has been shown that the small angle approach improved the performance of the PID controller, so that the stabilization is achieved in the presence of unknown frictions.

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