Experimental and Implementation of Robust Control Via Floating Air Levitation and Balancing Rotary Inverted Pendulum

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Abstract. This paper presents the implementation of robust control by using Programmable Logic Controller (PLC) for studying the behaviour of floating and balancing system. Floating Air Levitation system (FAL) and rotary inverted pendulum system (RIPs) module were designed and developed as the actual plant to investigate the performance of designed controller with the nonlinear systems. The objective of controller for FALs is to keep the height of a ball in the tube as the set point precisely, by adjusting the velocity of air flowing passing through the ball. For RIP, the objective is to stabilize the pendulum in upright position. Both plants can provide either the displacement or angular position by various type of sensors: ultrasonic and encoder. In this work, Proportional, Integral and Derivative (PID) and sliding mode controller (SMC) were implemented in OMRON NX1P PLC by using SYSMAC studio software for monitoring and control. The experimental results showed the comparison of PID and SMC performance. SMC presented a robustness response and low oscillating error depend on controller.

1. Introduction

The important issue of studying in control system by mathematical model simulation is the error from un-matched parameters and dynamic system, then the implementation with actual plant is the best practice. However, the practical system such as aircraft, helicopter and drone are difficult for the experimentation due to high operation cost and fatigue, so miniaturization has been used. One of the most interesting plants for investigating the fluid dynamic and control is Floating Air Levitation System. Many research works have been developed and applied Air Levitation System in several purposes. [1] proposed the measurement method and tracking algorithm automatically, in order to find the velocity of a falling ball in a tube for tested liquid. [2] proposed Fuzzy-PID controller based on Dspace by regulating the speed of a fan to keep a Ping-Pang ball at a predetermined position in tube. For education purpose, [3] demonstrated the use of the ball-in-tube experiment for introducing the fluid dynamics course. [4] proposed the control method of two balls inside the interconnect vertical tubes. For stabilization case, many previous works applied Rotary Inverted Pendulum system (RIPs) to verify the robustness performance of controller. [5] proposed the parallel distributed compensation (PDC) based fuzzy controller using linear quadratic regulator (LQR) technique to control RIP system. [6] proposed the mathematical model of rotary-rotary-planer inverted pendulum system. Programmable Logic Controller (PLC) is a key of automation in industry for calculation and computation. It can be programed by using...
the standard language such as ladder diagram (LAD), Instruction List (IL), Structure Text (ST), Sequential Function Chart (SFC) and Function Block (FB). Many previous work employed PLC to supervise and control machine systems in various fields. [7] presented using PLC to model and simulate tooling in the robot cell. [8] proposed using PLC to design water filling system in simulator tool. [9] proposed the application of using PLC as an automation transfer switch for PV power plant. [10] proposed using PLC to control a trajectory tracking of position for classification products using image possessing.

PID controller is one of most controllers for widely used in industrial control application such as position control [11], speed control [12], force control [13]. However, an optimal gain PID controller were required for improving stability. SMC controller is applied for robust to changes in the parameters in process, machine nonlinear system and disturbances. The SMC controller favours for control nonlinear system by applying a discontinuous control signal. Several nonlinear systems can be applied with SMC; the gun position servo system [14], vehicle heat pump air conditioning system [15] and XY-planar inverted pendulum [16].

This paper focus design and implement of Air Levitation System (FALS) and rotary inverted pendulum system (RIPS) and improving robustness control performance of PID and SMC controller theory algorithms. The improving performance depend on, robust of stability and called error upon selection of the error from pendulum.

2. Case study for nonlinear process
The application control of nonlinear dynamics system, to study of this work is to provide to the improve analysis and representation of nonlinear control systems. Control theory methods require for maintain stability in nonlinear systems. Nonlinear models currently available are linear, dynamics of linear systems could not to describe many commonly process. The control parameter such as force, position, speed, flows is use PID controller. However, the nonlinear control techniques can solve the problem of plants. In this work, floating air levitation and rotary inverted pendulum system were chosen for investigation.

2.1. Air Levitation System
Air Levitation System is an academic plant designed as an experimentation framework for teaching and learning aerodynamic and control engineering. This demonstration provides an insight into the system capabilities: the composition of hardware and software. According to the free body diagram in Fig.1, the Newton’s second law is used to derive the mathematical model of air levitation as (1), which $F_d$ is the lifting force, $m$ is mass of ball, $g$ and $a$ are gravity and the resultant acceleration, respectively.

$$\sum F = ma = m\ddot{x} = F_d - mg$$

![Figure 1. Model of air levitation system.](image)

The lifting force generating from the input air flow can be expressed as volume flow rate through the ball $q_{sp}$ can be expressed as (2), where $K_L$ is the positive constant and $A_{sp}$ is the cross-section area.

$$F_d = K_L V_{sp}^2 = K_L \left( \frac{q_{sp}}{A_{sp}} \right)^2$$

(2)
The volume flow rate through the ball is the summation of volume flow rate generating from the propeller, floating of the ball and the velocity of the ball.

\[ q_{sp} = q_{fan} - q_{red} - q_{rev} = k_x k_m u_m - k_x x_1 - A_p x_2 \]  

(3)

By substituting (2) and (3) into (1), then

\[ a = \ddot{x} = K_L \left( \frac{k_x k_m u_m - k_x x_1 - A_p x_2}{A_p m} \right)^2 - g \]  

(4)

Let's define the state \( x = [x_1 \ x_2]^T \) where \( x_1 \) is the ball’s position and \( x_2 \) is the ball’s velocity, then the air levitation represented in the state-space form can be written as (5) in which \( y \) is the measured position.

\[ x = \begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} K_L \left( \frac{k_x k_m u_m - k_x x_1 - A_p x_2}{A_p m} \right)^2 - g \\ x_2 \end{bmatrix} \]  

(5)

\[ y = C x = [1 \ 0] x \]

The air levitation system is a one of the popular plant process for studying control because the structure is simple and easy to use for experiment. The air levitation system was developed for PLC training kit, as shown in Fig. 2. It consists of the plastic tube with infrared sensor on the top to measure the ball position. The propeller was installed below to generate the air flow, which the flow rate can be adjusted by controlling the speed of motor.

![Air levitation system training kit](image)

**Figure 2.** Air levitation system training kit.

2.2. Rotary inverted pendulum system

Rotary inverted pendulum training kit consists of the rotating arm, which is driven by a DC motor inside the base, and a pendulum joint installed at the end of the arm for attaching an inverted pendulum link. The incremental encoder attaching at the joint was used to detect the deviation of angular position of the inverted link. Then the controller adjusts the power of motor to rotate the arm, in order to stabilize the inverted link at the upright position. The mathematical model of rotary inverted pendulum can be written as (6) in the state-space form. Let’s define the state \( x = [x_1 \ x_2 \ x_3 \ x_4]^T \) where \( x_1 \) and \( x_2 \) is the angular position and velocity of pendulum’s and rotating arm’s, respectively, \( u \) is the motor command, then the linearized dynamical model \[ 17 \] is given in (6) – (9)

\[ \dot{x} = Ax + Bu + D \]  

(6)

\[ A = \frac{1}{af - c^2} \begin{bmatrix} 0 & af & 0 & 0 \\ ah & -ac & 0 & -cd \\ 0 & 0 & 0 & af - c^2 \\ ch & -cC_2 & 0 & -df \end{bmatrix} \]  

(7)

\[ B = \frac{1}{af - c^2} \begin{bmatrix} 0 & ce & 0 & ef \end{bmatrix} \]  

(8)

\[ D = \begin{bmatrix} d_c(t) \\ 0 \\ d_c(t) \end{bmatrix} \]  

(9)
Whereas \( a = I_1 + mL_1^2 \), \( b = mL_2^2 \), \( C = mL_1L_2 \), \( d = \frac{k_1k_b}{R} \), \( e = \frac{k_1k_u}{R} \), \( f = I_2 + mL_2^2 \), \( h = mgL_2 \)

The rotary inverted pendulum system can experiment for balancing control and presented to real time control using controller for control robust target signal. The rotary inverted pendulum system is nonlinear system, the implementing the using Programmable logic controller (PLC). The Encoder sensor already applied to the measure angle velocity acceleration pendulum. The DC motor supplied power to balancing control pendulum rod. Experimental set up of the RIPS is shown in Fig. 3.

![Figure 3. Rotary inverted pendulum training kits.](image)

2.3. Experimental set up

The experiments setup present are of two process: to understand the basic concept of system, for example to control floating and balancing by PID and SMC controller. Experimental set up of the RIPS is shown in Fig. 4

![Figure 4. Experiment set up.](image)

3. Controller Design

Proportional integral derivative controller has been popularly used in control applications because of its simple structure as shown in Fig. 5. The controller was applied to stabilize the position level and pendulum angle equation expresses PID controller in time-domain which is resulting from the sum of proportional integral and derivative term.

\[
u(t) = K_p e(t) + K_i \int_0^t e(\tau)d(\tau) + K_d \frac{d}{dt}e(t)
\]

![Figure 5. Block diagram of experiments of PID and PD controller.](image)
Sliding mode control (SMC) is a nonlinear controller that switching control. There are two part in the SMC. Firstly, the part is a design surface. The second part, the forced to slide along the sliding surface to the equilibrium point, generally as zero state and its rate of change. The block diagram of SMC controller in stable- space model is shown in Fig. 6. Let’s define the sliding surface $s$ as

$$u = -\left(C^T B\right)^{-1} \left(-C^T Ax + k_s |s| \alpha \text{ sgn}(s) \right)$$ \hspace{1cm} (11)

Figure 6. Experimental preparation of real time control.

4. Experimental results
The experimental results represent that the floating air levitation and balancing rotary inverted pendulum can be used to controlling and improving of floating air levitation and balancing rotary inverted pendulum. PID and SMC controller is installing to control position level and angle pendulum. This study focusses the robustness response of controller efficiency in process system.

Figure 7. Experimental result of floating ball position control.

Figure 8. Experimental result of balancing rotary inverted pendulum.
The air levitation system with target position 5 cm and 10 cm are shown in figure 7. The results of position level control from determining of the position level by the distance sensor. Thus, we can determine the position response of the ball. Figure 8 shows the experiment of rotary inverted pendulum stabilization. At the beginning of experiment, the pendulum link was manually set at the upright position, then activated the balancing controller at PLC. Table 1 and 2 shown result of floating ball position control and balancing rotary inverted pendulum.

### Table 1. Result of floating ball position control.

| Controller | Target set point | 5 cm | 10 cm |
|------------|------------------|------|-------|
|            | Transient response |      |       |
|            | Dead time (s)     | 2.70 | 0.50  |
|            | Delay time (s)    | 0.30 | 0.40  |
|            | Rise time (s)     | 0.45 | 0.65  |
|            | Peak time (s)     | 1.40 | 1.00  |
|            | Overshoot (%)     | 181.8| 24.49 |
|            | Settling time (s) | 10.90| 3.10  |
|            | Settling min (%)  | 57.54| 13.28 |
|            | Settling max (%)  | 181.8| 24.49 |
|            | Steady state response | |       |
|            | Average error + (cm) | 0.40 | 0.49 |
|            | Average error + (%) | 39.50 | 4.90 |
|            | Average error - (cm) | 0.57 | 0.57 |
|            | Average error - (%) | 5.70 | 0.90 |

### Table 2. Result of balancing rotary inverted pendulum.

| Angle | Controller | P | PD | PID | SMC |
|-------|------------|---|----|-----|-----|
| Time of balance (s) | 5.5 | 9.15 | 13.7 | 21.14 |
| Average error + (degree) | 4.86 | 2.09 | 1.53 | 2.99 |
| Average error - (degree) | 5.05 | 1.92 | 1.37 | 2.86 |

The experiment is operated with real-time control using PLC, the PID and SMC controller have use to verify the position level and angle pendulum. The closed-loop control shown that the presented stability and robustness for compare method to improves efficiency.

5. Conclusion

This paper proposed compare PID controller and sliding mode controller for control of the air levitation and the rotary inverted pendulum systems using PLC. The air levitation system is simply but nonlinear system and suitable for experimental platform to improving the controller. It is easy to create and modified solution for learn controller in control technologies, PLC can be suitable for programming and control, its popular for applies in factory, this paper present PLC based for experiment to improve robust performance for rescale experimental at industrial applications. As future work, the robustness of the both processes to be improved with controller. The advantage of using PID controller is its simplicity. It can apply to the actual air levitation and rotary inverted pendulum to verify the performance of the proposed control algorithm. The experimental results as given in experimental results for air levitation show that the maximum swing of PID controller over than SMC controller. It can be seen that the amplitude of fluctuation of the maintain level smaller than the result from PID. From the results, the proposed SMC was found robust to balancing angle of the pendulum compared to the PID method. The experimental results of rotary inverted pendulum from this study the presented sliding mode controller can control the inverted pendulum with higher robust performance more than PID.
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