Exploring the Ideas of "New Engineering" Education Reform for Programmable logic Controller Applications Oriented towards Engineering Practice

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Abstract: In recent years, with the continuous advancement of the "new engineering" construction reform, exploring ways to enhance students' initiative in teaching and integrating theoretical and engineering courses, in line with actual engineering needs, has been a priority in educational reform. This paper introduces a method for integrating PLC (Programmable Logic Controller) teaching with theoretical and practical courses by renovating experimental equipment. It also provides specific parameters for the experimental platform. Teaching events have shown that 78% of students can solve PLC application problems using the knowledge they have learned, and 93% of students give positive feedback on the practical reform. The implementation of this curriculum reform provides ideas for the reform of graduate education aimed at engineering applications.

Keywords: PLC Teaching; Particle Swarm Optimization; Zero Vibration Derivative

1. Introduction

In recent years, with the continuous ascent of China's manufacturing industry, the country has gradually shed its awkward position as the "factory floor" for the West and started to venture further on the path of independent research and development. There is a strong demand for innovative and versatile talents. The traditional PLC course setup in graduate education emphasizes application over theory, which is determined by the nature of PLC as an application tool [1-5]. Cultivating students' abilities to raise, analyze, and solve problems is the core of graduate education. Compared to undergraduate education, graduate education places more emphasis on the word "research." Therefore, graduate PLC courses should break away from the traditional undergraduate teaching methods that focus mainly on introduction and application. Instead, they should combine control theory, algorithms, and application scenarios to create a closed-loop experimental system for students that goes from application scenarios to theoretical models to testing tools and platforms. This involves further reforming the teaching based on existing foundations, allowing students to participate in applying knowledge from multiple disciplines such as PLC, control engineering, and intelligent control to meet practical application needs, mastering the ability to comprehensively solve engineering problems.

To address these issues in the experimental design process, a crane anti-sway experiment platform was designed. Due to limitations in class hours, the design of the experiment platform started with typical engineering problems, taking the sway problem of crane lifting as the research object, abstracting the crane model, establishing a front-drive system model, and using input shaping algorithm for vibration suppression. Since it is difficult to choose parameters for the input shaper, particle swarm optimization method was applied to achieve vibration suppression. This realized the whole process application from actual engineering problems to theoretical modeling to building an experiment platform to algorithm verification, truly going from practice to application. Furthermore, the B&R controller system that supports MATLAB-Simulink platform development was adopted, offering a friendly programming environment where simulation algorithms can be directly downloaded into the controller. This allows students to focus more on understanding algorithmic problems rather than debugging programming details. Through group experiments, students have proven that the experiments achieved good results.

2. System Modeling and Experimental Platform Construction

2.1 Abstraction of the Mathematical Model

The operation of a crane is typically carried out in three-dimensional space. However, since this article primarily focuses on how to address the issue of cargo sway during the startup and stopping processes, a two-dimensional crane sway model has been established, as shown in Figure 1:

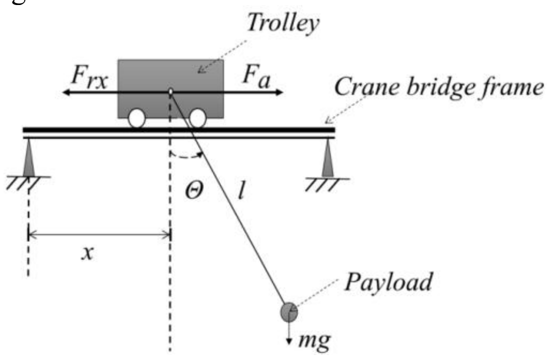

Figure 1. The Mathematical Model of Crane

Using the Euler-Lagrange equation, under the premise of not considering air resistance and the mass of the sling, the following mechanism modeling is carried out for the two-dimensional bridge crane:

$$\begin{cases}(m+M)\ddot{x}+ml(\ddot{\theta}cos\theta-\dot{\theta}^2sin\theta)=F-F_r \\ mlcos\theta\ddot{x}+ml^2\ddot{\theta}+mglsin\theta=0\end{cases} \quad (1)$$

In the formula, M represents the trolley mass, m is the load mass, the length of the hoist rope is l, F denotes the force applied to the trolley, and F_r is the resistance faced by the trolley. x、$\dot{x}$ and $\ddot{x}$ sequentially denote the position, velocity, and acceleration of the trolley; θ、$\dot{\theta}$ and $\ddot{\theta}$ sequentially represent the angle of the load's swing, the angular velocity, and the angular acceleration of the load.

During the control process, since the swing angle is usually less than 10°, the following assumption is often made to facilitate model calculation: $\sin\theta \approx \theta$, $\cos\theta \approx 1$. Thus, equation (1) simplifies to:

$$\begin{cases}(m+M)\ddot{x}+ml\ddot{\theta}=F-F_r \\ \ddot{x}+l\ddot{\theta}+g\theta=0\end{cases} \quad (2)$$

2.2 Model Characteristics Analysis

After obtaining the mathematical model, it is necessary to analyze the model itself. The analysis should integrate classical control and mechanics knowledge, combining multiple disciplines. The model serves as a means for students to deeply understand the characteristics of the controlled system, which helps in designing targeted control methods.

By applying the Laplace transform to equation (2), assuming the initial conditions of the system are zero, we obtain the system transfer function from equation (2):

$$\frac{s^2}{s^2l+g}X(s)=\theta(s) \quad (3)$$

From equation (3), we can determine:

(1) There is a linear relationship between system displacement and swing angle, meaning that controlling the second derivative of displacement (acceleration signal) can achieve the objective of controlling the swing angle.

(2) The acceleration signal and swing angle represent a typical second-order system; in the absence of damping, the system's damping ratio and natural frequency are evident.

(3) By altering the damping ratio, we can modify the oscillation duration of the pendulum swing, even achieving vibration-free conditions. Through analyzing the system model, students gain a clearer understanding of the system's nature and control methods, laying the groundwork for further problem-solving.

3. Control Model Construction

Based on the mathematical model, a control test box is constructed, which is divided into two parts: the mechanical and motor section on the front, and the electrical part on the back. The entire apparatus is installed and fixed within a specially made electrical cabinet with a simple and practical layout, facilitating user learning and operation. The electrical cabinet features an aluminum frame with a fully transparent structure and is equipped with safety door mechanisms to enhance operational safety.

The test bench utilizes a B&R ACOPOS servo drive to control the B&R motor, which moves the cart along a linear guide rail. An encoder mounted on the cart's pendulum is used to detect the position of the pendulum weight. The control panel on the front of the device enables convenient control of the cart's motion. The test bench consists of a mechanical system and a control system, designed to simulate the control of crane swings under actual working conditions. The specific mechanical system model is as Figure 2.

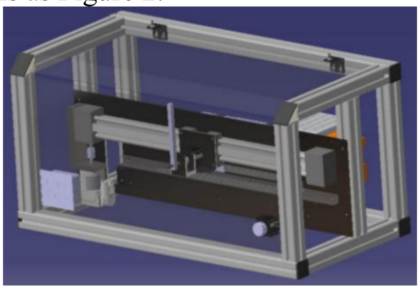

Figure 2. 3D Model of the Test Box

In the model, the guide rail and screw simulate the track on which the trolley operates. The slider combined with an aluminum plate forms a sliding plate that mimics the trolley, while the swing rod imitates the pendulum, and the weights fixed to the swing rod represent the load. The servo motor drives the sliding plate through a toothed synchronous belt, achieving control over the swing angle of the swing rod. The model parameters are as Table 1.

Table 1. Design Parameter Table

Parameter	Rail Length	Maximum Travel	Speed Range	Acceleration Range
Design Indicators	1000mm	500mm	1.5m/s	$5m/s^2$

To meet the above design performance indicators, an is selected, with the specific an appropriate servo drive system is selected, with the specific model as Table 2:

Among them, the most critical controller is selected from B&R's X20CP1382 series PLC. Its main feature is support for Matlab-Simulink hybrid programming. Modules simulated in Simulink can be directly downloaded to the controller,eliminating the need for discretization and code implementation processes, allowing students to focus more on understanding the algorithms.

Table 2. Selection Parameter Table

Device Name	Manufacturer	Model	Quantity
Servo Drive	B&R	80VD100PS.C02X-01	1
Motor	B&R	8LVA13.R0015D000-0	1
Encoder	OMRON	E6B3	1
24V Power Supply	B&R	0PS1050.1	1
80V Power Supply	B&R	0TP630.10	1
Operation Panel	B&R	4SIM.10-01	1
Controller	B&R	X20CP1382	1

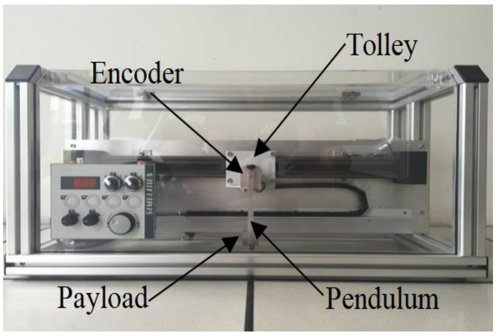

Figure 3. The Experiment Platform

The assembled test box is shown in Figure 3. After experimental testing, the laboratory effectively simulated the pendulum swing issues during the start-stop process in actual crane systems, providing students with an experimental platform for learning.

4. Case Design

To assist students in comprehensively and deeply understanding the integration of PLC with advanced algorithms, the first step involves having students conduct research to identify control algorithms. They then decide to use an input shaper method for vibration suppression and employ the PSO(Particle Swarm Optimization) algorithm to optimize the parameters of the input shaper.

4.1 Principles of Particle Swarm Optimization (PSO) Algorithm

Particle Swarm Optimization (PSO) is a population-based intelligent numerical optimization algorithm inspired by the study of bird flocking and hunting behaviors. The distinctive feature of PSO lies in its reliance on information sharing and collaborative cooperation among particles within a swarm to seek out optimal solutions [6-9]. Each particle possesses two attributes: position and velocity. The fitness value, calculated based on the objective function, assesses the quality of the solution represented by the particle's current position. In each iteration, particles adjust their velocity based on their historical best position and the global best position within the swarm, then update their positions. The basic iterative formulas of the PSO algorithm are as follows:

$$v_{id} = \omega v_{id} + c_1 r_1 (p_{id} - x_{id}) + c_2 r_2 (p_{gd} - x_{id}) \quad (4)$$

$$x_{id} = x_{id} + v_{id} \quad (5)$$

In these equations, v_{id} represents the particle velocity, and x_{id} represents the particle position. ω is the inertia weight that influences the proportion of velocity inherited from the previous iteration. c_1 and c_2 are constant learning factors that affect the velocity proportion learned from individual iteration history and group collaboration, respectively. r_1 and r_2 are random numbers in [0,1], with random factors expanding the search range.

4.2 Input Shaper Algorithm and Experimental Design

Input shaping technology is currently the main method adopted in open-loop swing control research for cranes. Its basic idea is to reduce residual system vibration by shaping the input signal. Common methods include ZV (Zero Vibration), ZVD (Zero Vibration Derivative) and EI (Extra Insensitivity) input shapers, which have been proven effective in reducing residual oscillation angles in practical crane systems[10-13].

The text focuses on the ZVD input shaper as the research object. An input shaper is essentially a series of impulse sequences with different amplitudes and time delays. The expected system input, after passing through the input shaper and convolving with the impulse sequence, produces a shaped input that drives the system, hence the name "input shaper." For its shaping process, take a three-impulse input shaper as an example; its constraint formula is:

$$A_1 = \frac{1}{1+2e^{-\frac{\xi\pi}{\sqrt{1-\xi^2}}}+e^{-\frac{2\xi\pi}{\sqrt{1-\xi^2}}}} \quad (6)$$

$$A_2 = \frac{2e^{-\frac{\xi\pi}{\sqrt{1-\xi^2}}}}{1+2e^{-\frac{\xi\pi}{\sqrt{1-\xi^2}}}+e^{-\frac{2\xi\pi}{\sqrt{1-\xi^2}}}} \quad (7)$$

$$A_3 = \frac{e^{-\frac{2\xi\pi}{\sqrt{1-\xi^2}}}}{1+2e^{-\frac{\xi\pi}{\sqrt{1-\xi^2}}}+e^{-\frac{2\xi\pi}{\sqrt{1-\xi^2}}}} \quad (8)$$

$$t_1 = 0 \quad (9)$$

$$t_2 = \frac{\pi}{\omega\sqrt{1-\xi^2}} \quad (10)$$

$$t_3 = \frac{2\pi}{\omega\sqrt{1-\xi^2}} \quad (11)$$

Where, ξ is the damping ratio of the system, and ω is the resonance frequency of the system.

Thus, the traditional ZVD shaping algorithm $C(t)$ can be achieved by Equation 12.

$$C(t) = \sum_{i=1}^{3} A_i\delta(t-t_i) \quad (12)$$

Although the principle design of the input shaper is not complex, it involves many parameters whose selection lacks regularity. Therefore, it's necessary to utilize particle swarm optimization to determine these parameters. Among them, A_1, A_2, A_3, and the time delay parameter t are variables to be optimized. However, by synthesizing equations (6) through (11), we can see that the actual parameters to be optimized are only $\frac{\xi\pi}{\sqrt{1-\xi^2}}$ and t. By letting $K = \frac{\xi\pi}{\sqrt{1-\xi^2}}, T = t$, the optimization process becomes a matter of optimizing K and T, which significantly speeds up the optimization process. Additionally, since the controlled system is an open-loop system, we perform a transfer function transformation to move the input shaper after the controlled object. After a single signal excitation, the vibration signal is collected, and through online collection and offline optimization, optimal parameters can be obtained ultimately. The specific implementation steps are shown in Figure 4:

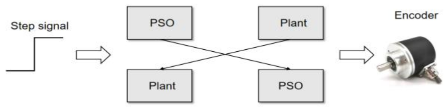

Figure 4. The Transfer Function Transformation

The next step is to construct the evaluation function. The evaluation function is the first step in the algorithm's optimization process. It needs to quantify the criteria for speed, vibration, and error while also being able to adjust the weight ratio among these three factors. The design method is as follows:

$$\begin{cases} e(t) = s_i(t) - s_e(t) \\ M_p = \max(e(t)) \\ J(t) = \int_0^{\infty} (\eta_1|e(t)|)\, dt + \eta_2|M_p| \end{cases} \quad (13)$$

Where, $s_i(t)$ is the value of the input signal at time t, $s_e(t)$ is he expected value of the signal at t, $e(t)$ is the error between the input signal and the expected signal at time t, M_p is the maximum error between the input signal and the expected signal, η_1 and η_2 are the weighted values, $J(t)$ is the final value of the evaluation function. The integral of $e(t)$ is used to describe the time and the average amplitude of adjustment. M_p is used to reflect the maximum magnitude of the amplitude. The penalty factors η_1 and η_2 are used to reflect the relation between $e(t)$ and M_p. The overshoot can be reduced by increasing η_2, but the response time will be extended.

Finally, the particle swarm algorithm is designed to optimize the input shaper. The optimization process is as follows:

(1) Initialization: Set up the relevant parameters of the particle swarm. This includes determining the number of particles m the dimensionality of the search space D, the range of the search space, learning factors c_1 and c_2, the range of inertia weights, local and global optima, and randomly initializing each particle's position and velocity. Also, set the related parameters for the command shaper based on experience to simply determine the parameter range.

(2) Fitness Function Calculation: Calculate the fitness value for each particle based on the problem's fitness function.

(3) Particle Best Position Update:Compare each particle's current fitness value; if it is less than the best position experienced, update it as the current best position.

(4) Global Best Position Update: For each particle's current fitness value, if it is better compared to the best position in the population, update it as the current best position.

(5) Velocity and Position Update: Update the particle's velocity and position according to the particle velocity and position update formulas.

(6) Termination:After reaching the set number of iterations, end the rolling optimization process and output the optimized parameter values.

4.3 Experimental Procedures

Firstly, a step signal is used to excite the system, and the resulting response curve of the system is shown in the Figure 5:

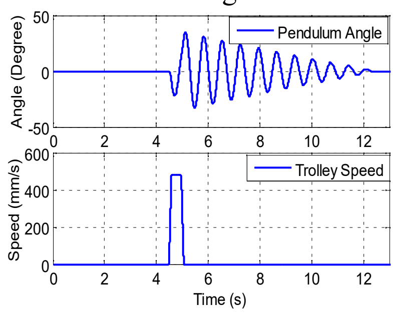

Figure 5. Pendulum Angles Recorded at the Trolley's Speed of 480 mm/s.

Then, the particle swarm parameters for the optimization algorithm are constructed as shown in Table 3:

Table 3. Initial Parameters of PSO

Number	parameter	Value
1	w	0.6
2	c_1	2
3	c_2	2
4	Dimension	2
5	η_1	1
6	η_2	1

Optimization of the K and T parameters yields the parameter variation curve and the membership function curve as shown in the Figure 6.

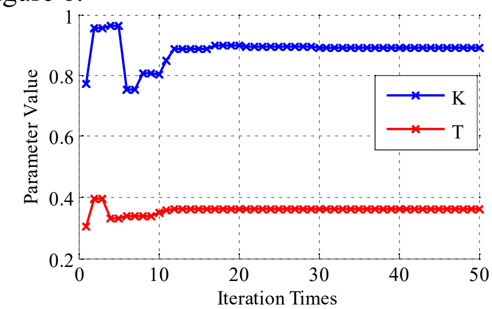

Figure 6. Optimization Curve of K and T

Here, it is especially important to emphasize to the students the correspondence between the changes in the membership function shown in Figure 7 and the optimization parameter changes, enabling them to understand the process of particle swarm optimization.

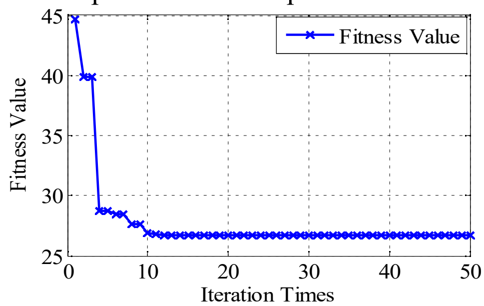

Figure 7. Fitness Curve of PSO

Ultimately, the optimal parameters K and T are obtained, with K=0.8952 and T=0.3626. An input shaper is built in Simulink, and through the Simulink program conversion function of the B&R system, the program is directly downloaded to the controller. The effect before and after adding the input shaper is compared as shown in the Figure 8.

The Implementation Process of Experimental Teaching

Based on the relationship between the teaching content and the knowledge points in the "PLC

Control" textbook, it is necessary to provide a targeted list of classroom guided learning tasks before starting the class, as shown in Table 4.

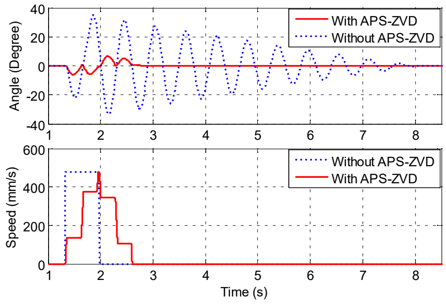

Figure 8. The trolley Speeds and Pendulum Swing Angles with and without APS-ZVD Algorithm

Table 4. PLC Crane Vibration Suppression Method Parameter Optimization Case Study Guide List

Learning Objectives	Train students to solve practical engineering problems through the combination of PLC and control algorithms.
Key Points	Obtain the parameters of the input shaper
Task one	Design the ZVD (Zero Vibration Derivative) input shaper
Task two	Particle Swarm Optimization (PSO) of parameters
Task three	Validation on the actual system

The following are the five implementation steps for experimental teaching.

(1) Step 1: Grouping for the experiment: All students are grouped into teams of 3 to 4 members, with one team leader elected who is primarily responsible for task distribution and communication coordination.

(2) Step 2: Experimental guidance: The experimental instructor, based on the grouping situation, clarifies the progress and specific requirements of each group's experimental project.

(3) Step 3: Collecting materials and analyzing the experiment: Each group member, according to the experimental requirements and the division of labor arranged by the team leader, collects materials, communicates, and completes the experimental project.

(4) Step 4: Mid-term assessment of the experiment: According to a predetermined mid-term assessment time, each group leader summarizes the progress of the earlier experimental projects, difficulties encountered, and solutions. Afterward, the teacher asks questions, and the members answer. Finally, the teacher provides evaluation and grades for the mid-term assessment.

(5) Step 5: Final evaluation of the experiment: A final defense date is set, and each group completes an experimental design report based on their chosen project and submits it to the teacher. The teacher ultimately assesses the experimental design report, focusing mainly on the standardization of the report, the approach to analyzing and solving problems, the feasibility and completion of the experimental project, and other aspects. Finally, the total grade is given based on the mid-term and final assessments.

5. Conclusion

The completion and evaluation of the experiment are shown in Figure 6. Looking at the learning outcomes of a certain class from our college, 78% of the students utilized the knowledge of PLC and related algorithms to complete the required experimental projects, 10% essentially completed the projects, while 12% did not finish. 93% of the students gave positive feedback about the course, and 7% rated it as good, providing suggestions for improvement based on their personal experiences.

The experimental case teaching of input shaper optimization design based on PLC algorithms has changed the traditional teaching model that primarily relies on classroom instruction by teachers. In teaching activities, by integrating case knowledge points with engineering requirements, students were able to adjust more complex control model parameters and observe, analyze, and scientifically record experimental data. Through a team collaboration model, team members could perform their duties, comprehensively address suggestions related to experimental case teaching, organize, manage, and coordinate various resources, fulfill their roles within the team, and support the observation points related to the connotations of professional accreditation.

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