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Practice-Oriented Intuitive Approach for Engineering Undergraduates: A Case Study*

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Although mathematical illustrations are widely used to explain concepts in control engineering education, however it appears somewhat difficult for some students to understand in the initial stage and then results in reducing of their learning enthusiasm. We noticed that students have huge interesting and active attitudes about experiment. In this paper, we introduced the experiment of point-to-point movement, typically in manufacture industry, for the students with no any control knowledge. Based on the principles of traditional rotary motors, students are guided to design a linear motor platform. The linear motor moves from zero position to a desired position. Students are requested to do their best to design a controller based on their intuitions and experiment results. The results and problems occurred will encourage students to study control knowledge and back to solve the problems. This practice-oriented intuitive approach (POIA) offers an alternative to learning control theory from concrete experience, so students can grasp knowledge and relate control concepts to simple events. A case study is provided, which involves a team of five undergraduates with a project named linear motor driven inverted pendulum and controller design sponsored through the Undergraduate Research Program (URP) by China Agricultural University. The results confirm the effectiveness of the proposed method.

Keywords: engineering education research; experiments; intuitions; group work; case study

1. Introduction

Most control engineering education is still based mainly on old style lecture classes where a great deal of information is given to the students. In control courses, mathematical analyses such as differential equations, difference equations, Laplace transform, z-transform, state space, block algebra, and others, are used to explain and deal with control topics. This is beneficial for students with logical intelligence and abstract conceptualization [1]. However, the mathematical approach not only appears somewhat difficult and abstract for some students, but also can't catch students' interesting, especially at the beginning of control courses. In order to motivate the interesting of students, it is important to introduce other approaches to facilitate control learning in ways that are different from the mathematical approach.

In today's technologically advanced world, why settle for a book that isn't perfect for your course? Why not try more experiment? This paper proposed a practice-oriented intuitive approach (POIA). This work suggests a novel way to understand control concepts by their intuitions and concrete experiences through doing experiments before the mathematical analysis of the topics.

We introduced the experiment of point-to-point movement which is typically used in manufacture industry. The linear motor is involved in the system. The principle of linear motor is not complicated. Actually it works the same as that in rotating machine. By cutting the rotary motor along the radius open and flattening, one can get a linear motor. Based on the above information and given them the specifications like required thrust and current, students are guided to design a linear motor platform. This design experiment can reinforce the design skills of students in the process and make them clearly understand every parts for a close loop controlled system.

The linear motor moves from zero position to a desired position. For such a system, we would like to design a controller to meet the following specifications:

(a) A 2% band settling time less than 0.3 seconds for a travel distance.
(b) OS% less than 20%.
(c) Steady-state error less than 0.2%.

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Students are requested to do their best to get the control objectives based on their intuitions only. These experiments seek to facilitate the understanding of fundamental mechanisms through experimental practices including the implementation of plants (a linear motor driven motion platform, feedback encoders, amplifier and control devices, cables, and *etc.*) and designing and tuning of control strategies. These experiments can reinforce the design skills of students especially in instrumentation and control system. This POIA offers new environments, advantages, and resources to learning control theory from concrete experience, so students can grasp knowledge and relate the concepts to simple events.

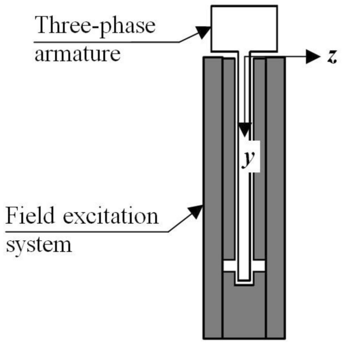
In the following sections, a case study is provided, which involves a team of five undergraduates with a project named *linear motor driven inverted pendulum and controller design* sponsored through the Undergraduate Research Program (URP) by China Agricultural University.

2. Linear motor driven precision motion platform

Permanent magnet linear synchronous motors (PMLSMs) are probably the most naturally applicable to applications involving high speed and high precision motion control, such as semiconductor processes, electronics board assembly, precision metrology and micro/nano motion control. PMLSMs enjoy the main benefits include high force density, high dynamic performance, low thermal losses, and most importantly, the high precision and accuracy associated with the simplicity in mechanical structure. Traditionally, the iron-core PMLSM gained more attraction because of the high developed motor thrust. However the thrust ripple is a major weakness of the iron-core PMLSM for precise positioning systems like what mentioned above. Recently, a specific type of linear motor, namely, the U-shaped ironless PMLSM (UIPMLSM) has been rapidly developed and gains attentions of engineers [2–5]. Generally speaking, the UIPMLSM inherits the benefits of PMLSM. And compared to the iron-core PMLSM, the UIPMLSM has advantages such as lack of detent force, no attracting force between the armature (or named as forcer) and the permanent magnets, and negligible iron loss, because it has symmetrical topologies of magnets and lacks primary iron core and teeth, shown in Fig. 1.

The direct driven UIPMLSM is used for the point-to-point movement experiment as all components are clear to the students, such as linear motor, feedback encoder, amplifier and control devices. Fig. 1(a) shows a schematic diagram of the UIPMLSM. It consists of the external U-shaped PM field excitation system and the internal three-phase armature. The U-shaped PM field excitation system is composed of back irons, which looks like a capital letter U, and face-to-face surface-type PM pieces. The back iron is ferromagnetic. The PM pieces are magnetized in the normal direction and mounted on the internal surface of the U-shaped yoke, facing the armature and arranging equably with symmetrical topologies and staggered magnetic poles N, S, . . . N, S, as shown in Fig. 1(b). The three-phase armature is an ironless winding layer in which the input current waveforms are sinusoidal and produce a traveling magnetic field.

Similar as the permanent magnet rotary synchronous motors, the thrust (named torque in rotary motors) is generated by the interaction between the permanent magnetic field and the traveling magnetic field, while the synchronous speed of the motor is the same as the speed of the traveling magnetic field [6]. The linear motor driven precision motion platform, students themselves implemented, is shown in Fig. 2(a). The tuning progress to get the desired results based on their intuitions is like the step response shown in Fig. 2(b).



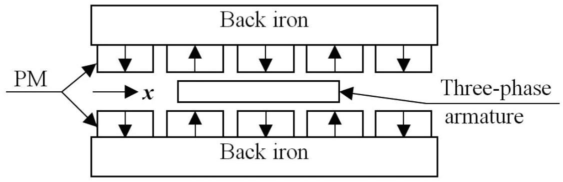


Fig. 1. Schematic diagram of the UIPMLSM.

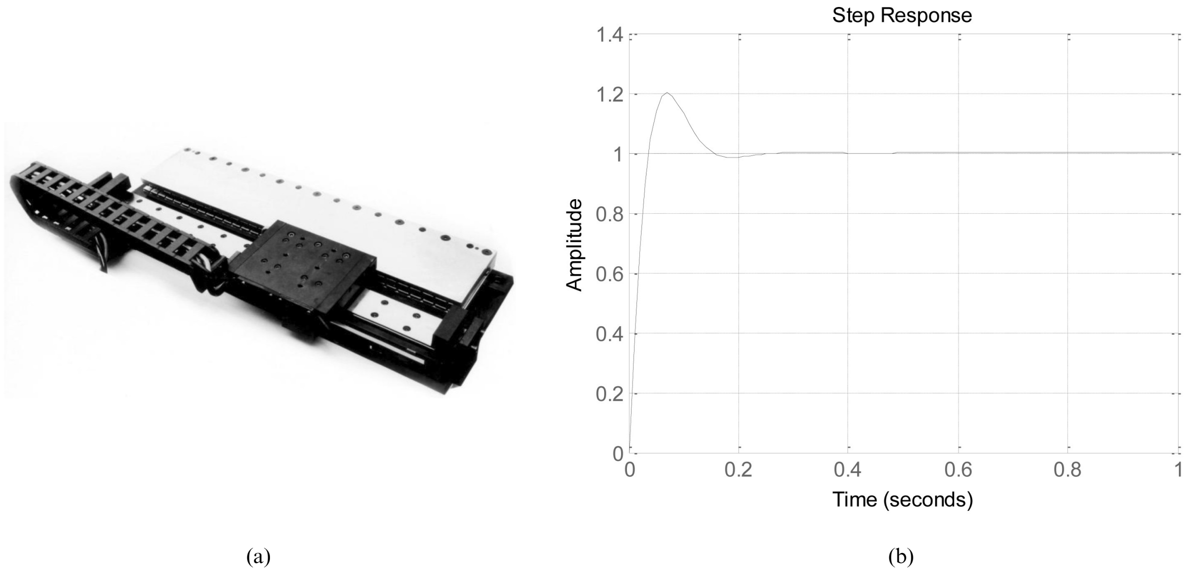


Fig. 2. The point-to-point movement experiment.

A very simple intuitive method is told the students at the starting. That is:

(a) We want to move the platform from A to a position of B, and then you send a small voltage of V_1.
(b) The platform may stop at a position with the position error e to B.
(c) With error e, ask the students how to cancel it?
(d) With intuitive idea, almost all students will add a small voltage in other direction to the system.
(e) That is right. But, how much?
(f) Ok, a simple P control can be introduced from here. That is $V_2 = P*e$.
(g) The above is a simplest method to get V_2. Tell the students, the target of the course is to get a best V to the system. We can exactly get the best value of V_2 and then tell the students we need control theory and the mathematical model of the motor and its driver.

They can easily relate the progress to a typical SISO feedback loop, shown in Fig. 3.

3. Direct driven inverted pendulum

One member of the team designed the direct driven inverted pendulum (dDIP) based on the UIPMLSM and assembled the system, shown in Fig. 4.

Inverted pendulum, noted as a non-linear, strong-coupling and natural instable system, has been widely concerned for a long time. Not only used as a teaching instrument, it is also studied in the spheres of theory and technology which are usually connected with precision instruments, robot control [7], human motion mechanisms [8], and advanced gravitational wave detectors. Although the inverted pendulum has been with us for almost several decades, it is still worth of studying.

The dDIP proposed in this paper, is a new member of the inverted pendulums. The conventional inverted pendulums, with their moving parts are usually driven by mechanisms of pulley-belt or lead screw connected to a rotary servo motor, are commonly influenced by adverse factors caused by mechanisms mentioned above. Pulley-belt brings lag effect while lead crew produces backlash when

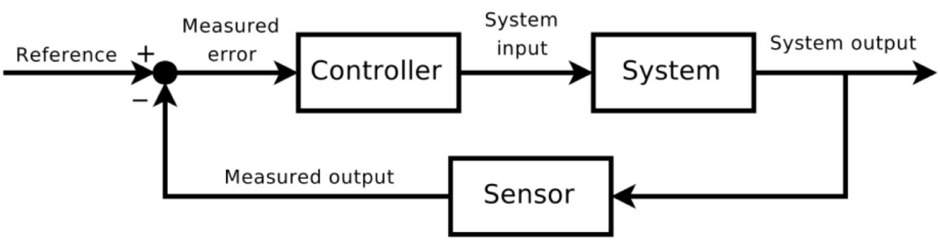


Fig. 3. A typical SISO feedback loop.

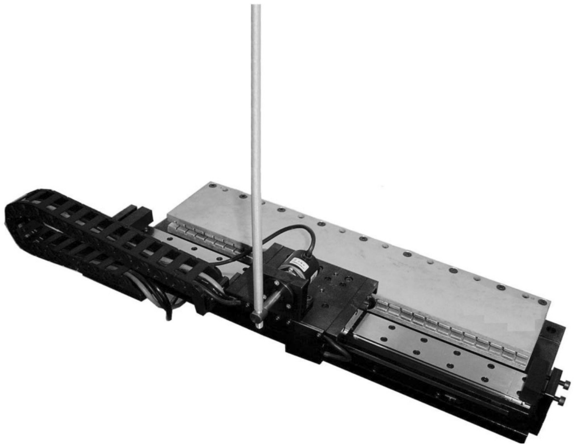


Fig. 4. Direct driven inverted pendulum.

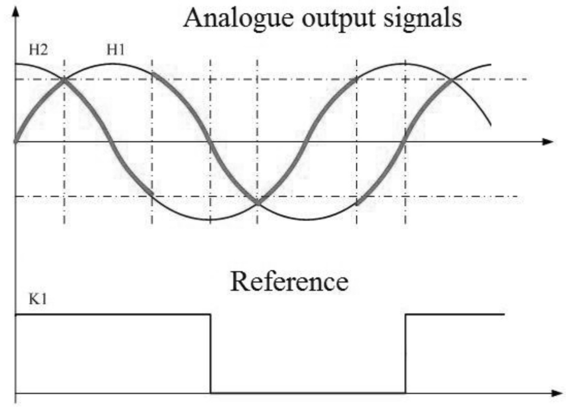


Fig. 5. The outputs of Hall sensors.

changing direction. Instead of using the ordinary driving methods, we directly drove an inverted pendulum with a linear motor which could effectively reduce or eliminate those disadvantages, and we named it as dDIP. Its mathematical model is analyzed and a corresponding control system is built.

4. Precise position detection technique

Most of the commercialized linear synchronous motor control systems employ the optical grating as their position feedback part and the linear encoders determine the precision and resolution of the system. However, the straightforward use of such a feedback sensor results in high cost and complicated configuration. To same extend, the linear encoders affect the application of linear motors. In recent years, the position sensorless control technology develops rapidly. This method resolves the position information on the basis of the relations between the motor electric parameters and the mover position. Nevertheless, as a result of limitations on the large amounts of calculations and the unstable operations at a low speed *etc.*, very few algorithms apply to the full-speed range [9–11].

One member of the team developed a novel method to detect motor position for the UIPMLSM using one switching type and two linear Hall sensors generating one reference signal (K1) and two sine signals (H1 and H2) with 90º phase difference signals [12], as shown in Fig. 5. Based on detecting end side magnetic field of the UIPMLSM and combining with suitable digital processing, this method is simpler and easier to be realized without extra circuits that deal exclusively with analog signals. It can be used for real-time system. Its low cost is also of great value.

The position angle β in one interpolation period is obtained with the following relation:

$$\beta = \frac{1}{2}\arcsin(2|\bar{u}_1||\bar{u}_2|), 0 \leq \beta < \pi/4 \qquad (1)$$

where $\bar{u}_1, \bar{u}_2$ are the corrected output voltages of two linear Hall sensors, respectively.

Thus, the actual position angle $\bar{\beta}$ can be gained accurately by correcting with the principle showed in the Table 1.

According to zero-crossing detection, the number N of the interpolation period can be recorded. The initial positions of the linear motor is regarded as *the position zero point*. Thus, the incremental displacement S (mm) of the linear motor can be gained as:

$$S = (N/2 + \bar{\beta}/2\pi)\tau/N_o, 0 \leq \beta < \pi/4 \qquad (2)$$

Where N_0 is the multiple of interpolation, and τ is

Table 1. Position angle correction in one period

$\bar{u}_1$	$\bar{u}_2$	Relation	Angle range	Actual position Angel $\bar{\beta}$
+	+	$\lvert\bar{u}_1\rvert \leq \lvert\bar{u}_2\rvert$	$0 \sim \pi/4$	β
+	+	$\lvert\bar{u}_1\rvert > \lvert\bar{u}_2\rvert$	$\pi/4 \sim \pi/2$	$\pi/2 - \beta$
+	–	$\lvert\bar{u}_1\rvert \leq \lvert\bar{u}_2\rvert$	$\pi/2 \sim 3\pi/4$	$\pi/2 + \beta$
+	–	$\lvert\bar{u}_1\rvert \leq \lvert\bar{u}_2\rvert$	$3\pi/4 \sim \pi$	$\pi - \beta$
–	–	$\lvert\bar{u}_1\rvert \leq \lvert\bar{u}_2\rvert$	$\pi \sim 5\pi/4$	$\pi + \beta$
–	–	$\lvert\bar{u}_1\rvert > \lvert\bar{u}_2\rvert$	$5\pi/4 \sim 3\pi/2$	$3\pi/2 - \beta$
–	+	$\lvert\bar{u}_1\rvert \leq \lvert\bar{u}_2\rvert$	$3\pi/2 \sim 7\pi/4$	$3\pi/2 + \beta$
–	+	$\lvert\bar{u}_1\rvert > \lvert\bar{u}_2\rvert$	$7\pi/4 \sim 2\pi$	$2\pi - \beta$

the magnetic pitch of PMLSM. Students will be clear of the feedback encoder in this progress.

5. Control algorithms and hardware-in-loop control system

Inverted pendulum, noted as a typical non-linear system, can be analyzed and controlled by state-space functions with a non-linear controller. Our goal is to find out the performance and characteristics of dDIP, especially the differences between a conventional one and ours. In order to achieve the desired performance, the team employed some control theories based on their experience and study, especially the pole placement, LQR [13], cascade PID [14], and adaptive neural network fuzzy inference system. And they build the hardware-in-loop control system by using dSPACE and their own-designed control signal processing and control engineering (cSPACE).

Figure 6 shows the hardware architecture of IP and LSM. Dozens of strategies can successfully keep a pendulum staying inverted, for instances, the well-known LQ, fuzzy control [15] and neural network strategies which are commonly appeared in literatures. It is known that PID controller is one of the most widespread controllers in industrial applications [16–17], and its tuning procedure is easy and direct. Thus, one member adopts the conventional PID control as our testing measure. The PID controller is able to be transplanted to different

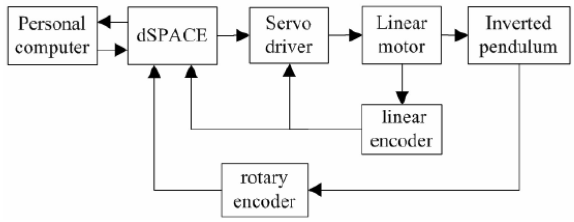
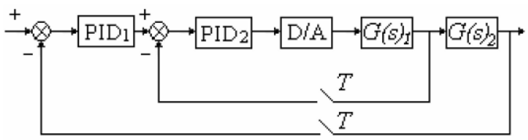


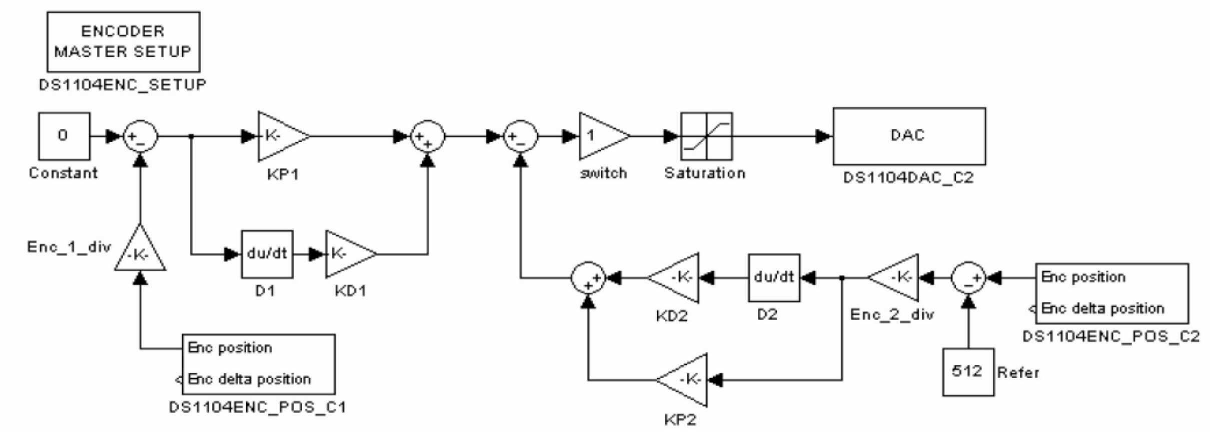
Fig. 6. Hardware architecture of the IP and LSM.

systems. It is mentioned that we have regarded the dDIP as a single input and double output system. Therefore, it seems that PID strategy cannot solve the problem properly as a kind of classical control theory. However, we have a widespread-used method to make it possible, the cascade PID controller. A typical cascade PID controller is shown as Fig. 7(a). The two transfer functions, $G(s)_1$ and $G(s)_2$ represent the input and output relations of input force between pendulum angle and cart position respectively.

The procedure of dSPACE control could be implemented as follows. When the system gets started, a sample routine will acquire values from two encoders (linear and rotary encoders) and send them to dSPACE, and then they will be attenuated respectively in order to keep in the same order of magnitude because the original readings of the linear encoder is much bigger than the rotary encoder's. Then the cascade PID operation will be applied. Finally the DAC block of dSPACE will



(a)



(b)

Fig. 7. dSPACE-based dPIP control flow diagram of cascade PID controller.

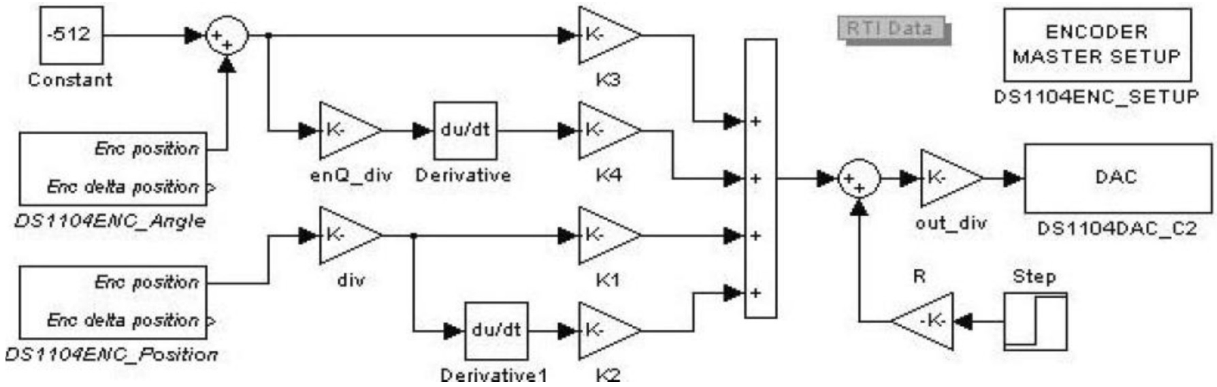


Fig. 8. dSPACE-based dPIP control flow diagram of LQR controller.

send the signal in form of voltage to the motor driver, which always amplifies the control signal it receives. In this way, the linear motor moves within a small range of distance, and keeps the pendulum standing upright. The realistic control routine can be built simply by modifying the simulation part that previously stated, shown as Fig. 7(b). Another member designs a LQR controller as shown in Fig. 8. And, the dDIP is successfully controlled by a dSPACE controller and also a TI28DSP based cSPACE. The results show that the dDIP can be stabilized to its upright position and at the same time the cart's displacement can be also regulated to zero after exerting a step disturbance to the dDIP. Experiments show that the transition time is within 4 *s*, which indicates that dDIP has excellent dynamic response.

The results and problems occurred in the experiments will encourage students to study control knowledge and back to solve the problems. So students can learn control theory from concrete experience.

6. Conclusion

In this paper, the POIA is introduced to offer an alternative to learning control theory from concrete experience. This work suggests a novel way to understand control concepts by their intuitions and concrete experiences through doing experiments before the mathematical analysis of the topics. So students can grasp knowledge and relate the concepts to simple events. This work offers an alternative for students who learn better from concrete experiences.

A case study is provided, which involves a team of five undergraduates with a project named linear motor driven inverted pendulum and controller design sponsored through the URP by China Agricultural University. These undergraduates get lots of control concepts from this program and their intuitions and understand the control concepts better than learning from the lecture only. And they can reinforce their design skill and improve their teamwork ability in the process. The results confirmed the effectiveness of the proposed method.

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