The Inverted Pendulum Problem as a Senior Design Project

Robert Lynn Mueller
The Pennsylvania State University
New Kensington Campus

Abstract

The 4-year baccalaureate degree in Electro-Mechanical Engineering Technology at Penn State New Kensington requires a project design course in the senior year. It is a capstone course that allows the students to apply the engineering principles encompassed in the courses that lead up to and include the senior year. A recent project was the so-called inverted pendulum problem. It consists of wheeled base with a vertical pendulum hinged on top of the base. The control system must move the wheeled base as required to keep the pendulum in a vertical position within a certain tolerance. While a working device can be purchased, a lot can be learned by building the device from scratch. In addition, there are also many papers published regarding the modeling and theoretical control of the system, but there is very little regarding the actual implementation of the mechanical device or its control system. These students encountered several problems in the selection of the overall mechanical design, the appropriate position measuring device, the final control elements, and the control algorithms. The focus of this paper is to describe the design, construction, testing, and lessons learned from this project.

Introduction

The senior project is a capstone project course taken in the final term of the 4-year Bachelor of Science in Electromechanical Engineering Technology (BSEMET) degree offered at Penn State University New Kensington. The objectives of the course are to train the students in project management, communication skills (both written and oral), budgeting, application of engineering skills, and team building. Each project team consists of 2 students (or one team of 3 if the course has an odd number of students) and the students are allowed to pick their own teams. The team is usually responsible for selecting its project with the condition that the project must contain at least 3 fundamental components: measurements from an electromechanical system, control decisions based on those measurements, and then the control of electromechanical elements to achieve some design criteria. One philosophy of the course is to let the students perform as much of the design work as possible even at the expense of them going down the wrong path on occasions.

During the first 2 weeks of the course, the student-teams work with the course instructors to discuss potential projects. For this term, the students were assigned projects. At beginning of the 3rd week each team must make a formal project proposal presentation. This presentation and written report account for 10% of the overall course grade. To accomplish the administrative objectives of the course, the project team must provide biweekly written and oral progress reports on project design-updates, schedule, and budget. This accounts for 25% of the course grade. At the end of the term, each project team is required to write a group project report detailing the project's design and budget; this accounts for 25% of the grade. A formal project presentation that includes a demonstration of the project is also required and this counts for 25% of the grade. Additionally, each student also writes a "journal-style" paper regarding one

particular technical aspect of the project. This contributes the remaining 15% of the course grade.

The BSEMET degree can be earned by going full time during the day or by going part time during the evening. Day time students typically build their projects on campus using materials and tools provided mostly by the university. Evening students usually have full time jobs as technicians or sometimes as engineers. They tend to build their projects off campus using materials and tools from their place of work. This can be a problem because the faculty cannot always monitor the projects as closely as required. This project was done by students in the evening program.

Description of Problem

One team of 2 students was given the following problem description:

Referring to Figure 1, a vertical pendulum is connected to the cart on a one-dimensional pivot. The cart must be controlled to keep the bar vertical within some tolerance. The disturbance is entered by giving the cart a step change in its horizontal position or by physically causing the bar to move from its vertical position. The cart may be mounted on a rail or be free-standing. The bar may be of any material and of any diameter, but must be at least three feet in length.

Figure 1. Conceptual Picture of Problem.

While a working device can be purchased [1], a lot can be learned by building the device from scratch.

The students selected performance specifications of settling time of 3 seconds and steady-state movement of less than 1.8 degrees (this corresponds to around 5 counts of the encoder that was selected). They also elected to build a free-standing wheeled cart that uses a physical movement to the bar for the disturbance.

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Before continuing on, it should be mentioned that the students were unsuccessful in getting the pendulum to remain vertical. The possible cause(s) for this will be addressed.

Figure 2. Finished Cart

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General Mechanical Assembly

Please refer to Figure 2. The students elected to use a four-wheeled cart. It is driven by a brushless DC servomotor with a pulley and belt system to drive one of the axles. The pendulum assembly is mounted to the center of the cart by a single pivot, which allows for approximately 30 degrees of total travel. Mechanical hard stops are used to restrict the pendulum's travel. The pendulum rod is a 1/4" x 36" steel rod.

Wheels

The first choice for wheels was hub-less molded plastic wheels. These proved too slick for the proposed running surface. They also lacked an easy means for mounting. The final wheels were fashioned after wheels used for radio controlled cars. They have a 7/16" splined shaft inserted into 3" wooden hubs. Placing 2 hubs together per wheel provides a groove that allows a 60A durometer rubber O-ring to be installed. These wheels provide maximum grip on a hard, smooth surface, but do not deform under load. The wheels are attached to the axle that is a 1/4" hardened steel rod.

Drivetrain Assembly

The drivetrain consists of a brushless dc servomotor with a 2.5" diameter pulley. The motor is mounted to the cart via a 1/4" plate steel mounting bracket fabricated for a NEMA 23 motor. The axle assembly has a 1" diameter pulley that connects to the motor's pulley via a belt. This may have also contributed to the problem because it probably should have been geared lower rather than higher. This would have allowed the motor to make larger movements for smaller changes in the cart's movement.

Motor

A rather unscientific approach was used to determine the necessary acceleration. The pendulum was balanced on a student's hand and it was estimated that an acceleration on the order of a few inches per second per second would be necessary. The next step was to determine a ball park motor size. This was done by first ignoring friction and inertia values for the wheels and pulleys. It was also assumed that the pendulum's inertia was small compared to that of the cart. Using a desired acceleration of 6 inches per second per second and a cart weight of 10 pounds, the necessary force on the cart F_c would be:

$$F_c = \frac{10 \text{ pounds} * 6 \text{ inch/sec}^2}{386.1 \text{ inch/sec}^2} = .16 \text{ pounds}$$

This would require the following torque on the axle T_a through the 3" diameter wheel:

$$T_a = .16 \text{ pounds} * 1.5 \text{ inch} * 16 \text{ oz/pound} = 3.84 \text{ inch-in}$$

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Taking this torque through the drivetrain assembly resulted in a motor torque T_m of:

$$T_m = \frac{1.25 \text{ inches}}{0.5 \text{ inches}} * 3.84 \text{ inch-oz} = 9.6 \text{ inch-oz}$$

This value was doubled to ensure that there would be enough torque to handle the friction and inertia that had been ignored. The motor used is one that was in inventory and is a CNC model BNL2315APGA which has 25 inch-ounce of torque.

Pendulum Position Measuring Device

There are a couple of ways to measure the position of the pendulum. One way is to connect a potentiometer to the pendulum's pivot shaft and then devise a circuit that makes use of the changing resistance as the pendulum rotates about the shaft. An encoder or resolver connected to the pivot shaft is also a possibility. These students selected a US Digital model S5D-1024-B encoder for the feedback device. This device has 1024 pulses per revolution which results in approximately 0.35 degrees per pulse. Since the steady-state specification was to hold the pendulum to within 1.8 degrees, it was thought that this encoder would provide sufficient resolution.

Motor Controller

A Pacific-Scientific PC 833 was selected as the motor controller. This was probably the downfall of the project. This controller was selected because one of the students used it at his place of employment and he was very familiar with its operation. It was thought that the encoder could be used to measure pendulum position and that could be used as pseudo feedback to act as motor position. Unfortunately, that was not the case. The motor is a servomotor with an encoder and Hall sensors for commutation. The servo controller can work effectively with this type of motor and feedback when the motor and encoder are on a common shaft. The controller uses the Hall sensors for commutation only during initial power-up. After 1/3 cycle of motion, the controller switches the commutation source to the encoder. It does this because with a high resolution encoder, smoother velocity control can be obtained. This is especially noticed at higher speeds. Since the encoder was already being used to sense pendulum position, the drive was unable to control the servomotor. This controller does allow the use of primary and secondary feedback if a resolver is used as primary feedback. This would allow a remote encoder to be used. However, a motor with resolver feedback could not be obtained before the end of the term.

Control Algorithm

The first attempt at finding the tuning parameters involved simulations using system model equations that are readily available [2] [3] [4]. This was done since conventional methods

(ultimate method or from a process reaction curve) of determining tuning parameters will not work [5]. However, when it came time to enter the parameters it was discovered that the Pacific-Scientific controller's parameters are expressed in Hertz. Since there was no apparent method to convert standard tuning values into the required Hertz-values, this effort was wasted time.

However, the Pacific-Scientific controller does allow the user to tune the servomotor by use of the self-tuning programs provided by the manufacturer. The self-tuning is accomplished by first downloading the motor parameters to the controller. The controller is first given a position step input to an unloaded motor. The controller is then given a step input with the motor connected to the cart. From this procedure, the parameters for the position and velocity control loops are calculated by the provided software. Since the project was not successful, it can't be determined if the parameters are correct but there is no reason to suspect that they are not.

Testing

The original test plan was to enter a disturbance to the pendulum by nudging or blowing on the pendulum. However, it was found that just by waiting the pendulum eventually moved on its own. And while the controller tried to make adjustments to fix the pendulum's position, it was obvious that the feedback was incorrect and the cart began making erratic back-and-forth movements.

Conclusion

This paper has discussed a senior project that involved students trying to implement the inverted-pendulum problem. In retrospect, the project may have been a little aggressive for a 14-week course. It may have been helpful to assign this same project all four of the teams that were taking the project course. This would have effectively had 8 people working on the project even though it would produce 4 separate but similar projects. However, while the students were not successful, the project ended up being a great learning experience for both students and faculty.

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ROBERT LYNN MUELLER

Robert Lynn (Doc) Mueller is an assistant professor of Electro-Mechanical Engineering at the New Kensington Campus of the Pennsylvania State University. He received his B.S. in Electrical Engineering from Wichita State University and his Ph.D. in Electrical Engineering from the University of Pittsburgh. He is a registered professional engineer in the state of Pennsylvania and a member of several professional societies. Dr. Mueller spent 30 years working with industrial control systems before joining Penn State and still continues to work as a consultant providing advice regarding industrial automation.