# Design of an Economical Student-built Automatic Control System

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## Abstract

Economical student-owned and built laboratory equipment is proposed as a means to increase student exposure to hand-on learning activities without the consumption of resources normally associated with offering a traditional laboratory course. The case presented is that of a course intended to expose students to the workings of an auto-pilot of a ship. It is shown that the mathematical basis behind a ball-and-beam control system is substantially the same as that behind a ship's auto-pilot, allowing the use of similar design processes for both. A bill of materials totaling less than $60 US is provided to allow students to build their own working models of the control system. A variation of the technique was piloted at the authors' institution with good success: all students who attempted to design a working controller were able to do so and successfully demonstrate it. It is concluded that the use of student-built laboratory equipment is a viable option for expanding the hand-on component of otherwise theoretical courses in at least some circumstances.


## Introduction

It is well established that laboratory or "hands on" activities facilitate increased levels of student learning and outcome achievement. The value of "learning by doing" has not only been document by several authors[6], but was also a central focus of Kolb's Theory and Learning Style Inventory[3]. In an engineering setting, the value of a laboratory component is thoroughly discussed by Feisel and Rosa[2], among others. However, the wisdom of such an approach was probably most succinctly expressed about 2,500 years ago by Confucius, as relayed by McCarthy[4]: "*I hear and I forget. I see and I remember. I do and I understand.*"

Programs have practical reasons for adopting laboratory activities as well, and among these rank the laboratory component's ability to contribute to the direct assessment of multiple student outcomes. Consistent with this, many programs seek ways to introduce such activities into their programs of study. As strong as these motivations are, programs may encounter the following obstacles to creating additional laboratory components for a program of study:

1) Space constraints
2) Faculty member time constraints
3) Student scheduling constraints
4) Financial constraints on the purchase of laboratory equipment

Even if these constraints are satisfied partially or completely, there is still an opportunity cost associated with each of these constraints; a program that is able to re-purpose or build new space for a laboratory, buy appropriate equipment, and then schedule both faculty and student time accordingly does so making the conscious decision that all of these finite resources are not going to be used for something else.

Theory:

Control theory may be applied in a marine engineering context as applied to the problem of maintaining a ship on a steady course. Consider a ship operating on the plane of the water's surface and viewed from above, as shown in figure 1.


**Figure 1: Top View of Ship and the Associated Free Body Diagram (right)**

The ship has a mass moment of inertia about its vertical axis *I*, and is subject to a turning moment *M(t)* from the ship's rudder. The angle of the ship relative to the earth's cardinal (inertial) directions is $\theta$. The ship also experiences damping from the water, which here is approximated as a linear function of the angular velocity $\dot{\theta}$. The differential equation of motion for such a system may be developed using appropriate techniques[1], and is given as equation (1).

$$I\ddot{\theta} + B\dot{\theta} = M(t) \tag{1}$$

A transfer function relating the transformed input moment *M(s)* to the transformed heading angle may be found using classical control techniques[1,5] and is given by equation (2).

$$\frac{1}{Is^2+Bs}M(s) = \Theta(s) \tag{2}$$

Such a system lends itself readily to Proportional – Integral–Derivative (PID) Control, and a simplified block diagram for such a control system using $\theta_i$ as the input (or ordered) ship's heading and the transfer function from equation (2) as the "plant" is shown in figure 2.

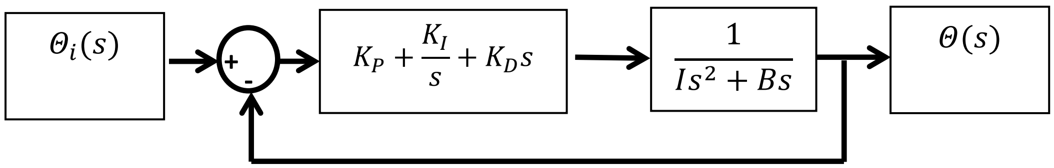


**Figure 2: Block diagram of PID Control System**

The system may be reduced to the "closed loop" system shown in figure 3.

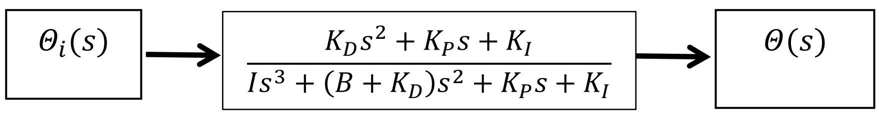


**Figure 3: Closed loop block diagram**

A comparison may be made to a "ball and beam" system consisting of a ball rolling without slipping on a track, the angle of which may be controlled by a motor or servo. Such a system and the corresponding free body diagram for the ball are shown in figure 4.

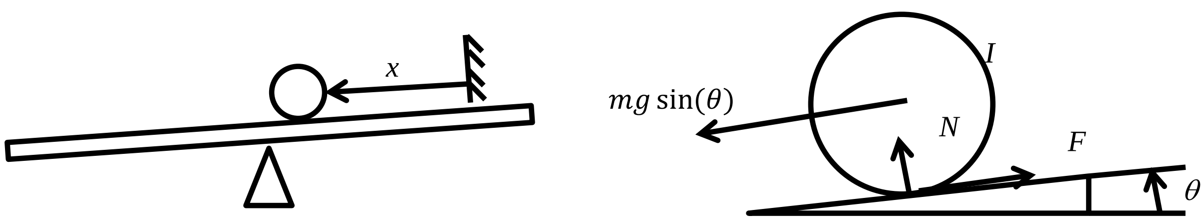


**Figure 4: Ball-on-Beam and Corresponding Free Body Diagram**

The differential equations of motion for the system shown in figure 4 are given as equations (3) and (4), where $r$ is the radius of the ball, $m$ is its mass, $g$ is the acceleration due to gravity, $x$ its position along the beam, $F$ the force of friction at the ball-beam interface, $N$ the normal force of the beam against the ball, and $I$ the moment of inertia of the ball. Observe that the angular displacement of the ball may be expressed in radians as $x/r$.

$$Fr = \frac{I}{r}\ddot{x} \tag{3}$$

$$m\ddot{x} = mg\sin(\theta(t)) + F \tag{4}$$

These equations may be combined and the friction force $F$ eliminated to obtain equation (5).

$$(mr^2 + I)\ddot{x} = mg\sin(\theta(t)) \quad (5)$$

With a small angle approximation ($\theta \approx \sin\theta$), and performing similar analysis as was done to obtain figures 2, and 3, the following closed-loop block diagram with PID control may be obtained:

$$\Theta(s) \longrightarrow \boxed{\frac{K_D s^2 + K_P s + K_I}{(mr^2 + I)s^3 + (K_D)s^2 + K_P s + K_I}} \longrightarrow X(s)$$

**Figure 5: PID control of ball-on-beam**

Careful comparison of the closed-loop transfer functions in figures 3 and 5 shows that they are identical with the exception of the simplified coefficient of $s^2$ in the denominator of the middle block of figure 5 and a more complicated coefficient of the $s^3$ term (which may be considered an equivalent inertia). This strong similarity allows the ball-and-beam to be used as a means to simulate a ship's auto-pilot.

Apparatus

The apparatus consists of the materials listed in table 1. Representative domestic purchase prices (without shipping) for individual components are provided in US dollars for those pieces that are not readily available as everyday consumer items. Brand or vendor names are merely illustrative and do not imply endorsement, and these lists should not be considered exhaustive.

Table 1: List of required materials

| Component | Price | Sources |
|---|---|---|
| 9g Micro servo | $5.95 | Mouser electronics, MiniIn TheBox, Gearbest |
| IR distance sensor (Sharp ® GP2Y0A02YK0F) | $14.95 | Karlsson Robotics, Acroname, MicroControllerShop.com |
| Arduino® UNO-compatible board | $24.95 | SemiconductorStore.com, Newark, Allied electronics |
| Electronics breadboard | $5.32 | Newark, Adafruit |
| 24 gauge hookup wire | | Electrical supply |
| Potentiometers (trimmer resistors—three required) | $2.08 ea | Mouser, Newark |
| Foam or wooden ball | | Craft supply store |
| Paper clip | | Office supply store |
| Adhesive tape | | Office supply store |
| Plastic ruler | | Office supply store |
| Card stock, manila envelope, etc. | | Office supply store |
| Cardboard or wooden base | | |

Students must also have access to a suitable computer equipped with software capable of writing an Arduino “sketch,” compiling it, and downloading it to the Arduino compatible controller. Code for the ball-and beam balancer using a “PD” algorithm is provided in appendix A.

The components may be assembled as shown in figure 6. The connecting link is a straightened paper clip. It is bent into a hook and threaded through a 1/16 inch (1.5 mm) hole drilled in the end of the plastic ruler at the top, and is bent in an “L” shape and inserted into the servo’s crank arm at the bottom. Figure 7 is a photograph of the completed apparatus, while figure 8 shows the detail of the connecting link. Local experimentation with the various components should be expected and encouraged.

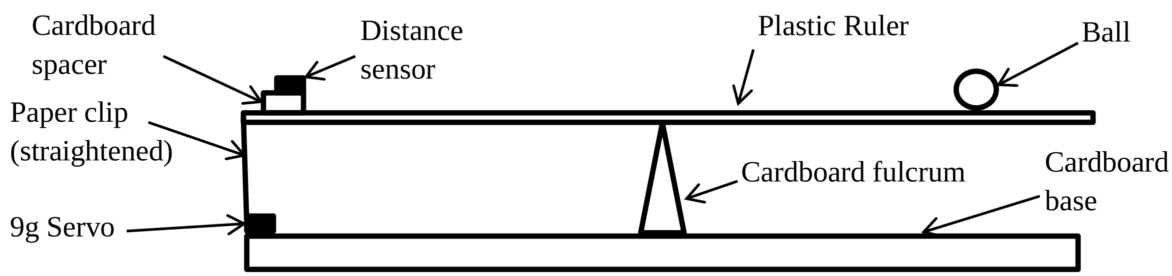


**Figure 6: Diagram of Ball-and-Beam Apparatus**

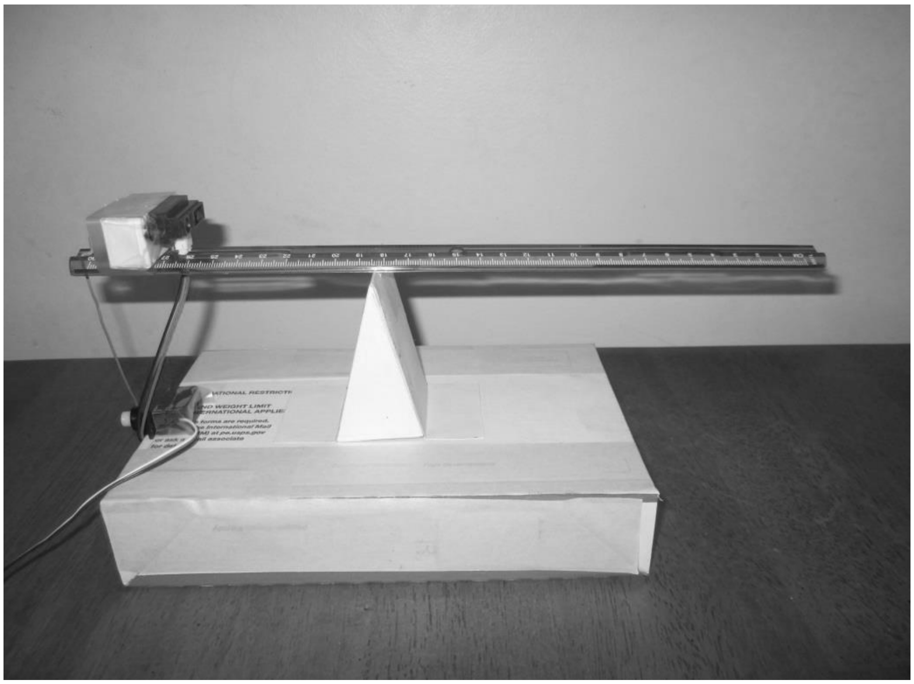

**Figure 7: Photograph of the completed apparatus**

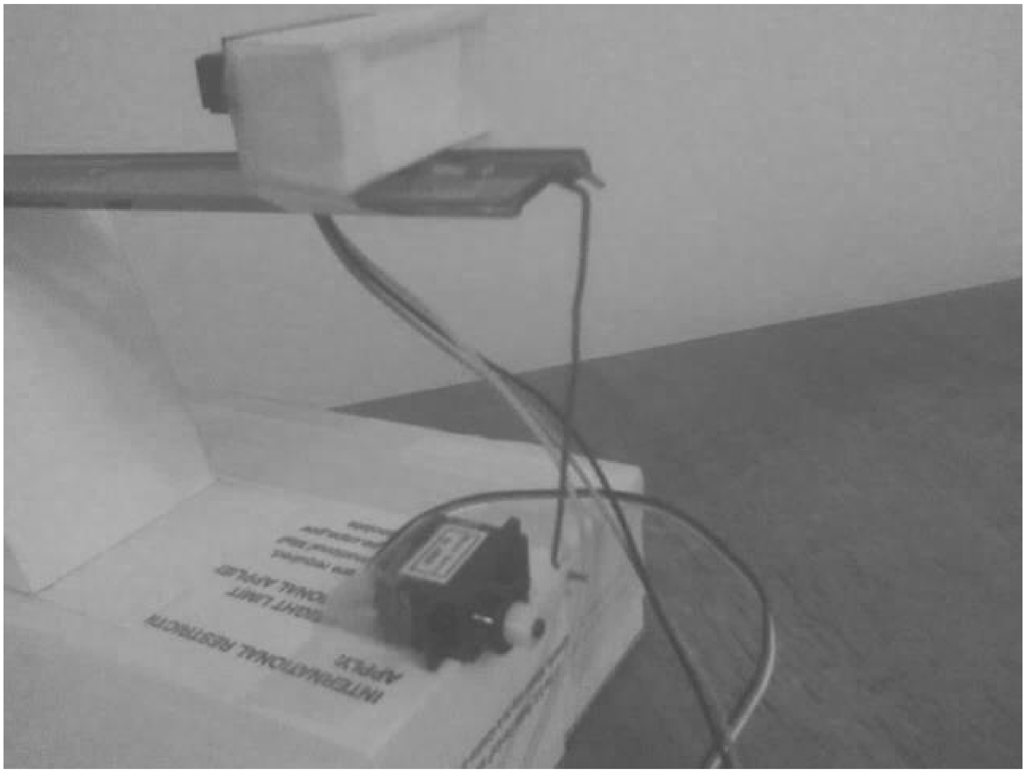

**Figure 8: Detail of the connecting link. The hook at the top end and the "L" shape at the bottom are both visible.**

## Results

Hardware similar to that shown in figure 6 was introduced to the students enrolled in a senior-level ($4^{th}$ year) modelling & controls course at the authors' institution. For the inaugural offering, the apparatus was built by the faculty, but the controller and associated circuitry was assembled by the students. The students had no previous formal computer programming experience, such as would be encountered in a typical undergraduate introductory computer programming course. Rather, the concepts of computer code development were introduced through a series of example problems of gradually increasing levels of complexity. For example, an early assignment required the students to write a code capable of turning an LED on and off at equal one second intervals. Subsequent assignments changed this to coded increased intervals (one second, two seconds, etc.) and ultimately to a variable interval determined by the position of a potentiometer. The "delaymicroseconds" command was introduced at this time, and the students repeated the process using pulse width modulation and a servomotor. The framework of the code that allows control of the servo through the position of a potentiometer

The project was presented in terms of a challenge: develop a controller that is capable of moving the ball on the rail-like beam as close to the end of the beam as possible without letting the ball drop. Maximum points (100) were awarded if the ball could be moved and held within 5 cm of the end of beam, 90 points were awarded if the ball came within 10 cm, 80 points if the ball came to rest within 15 cm, and no points if it failed to meet any of these benchmarks or if it overshot and fell off the beam entirely. The students were given the opportunity to practice with the equipment in advance and tune their personally-owned controllers through the use of the trimming potentiometers, which were used to adjust the various gains that were used by the student-written controller codes. Once sufficiently practiced, the students then demonstrated the function of their controllers for the instructor. Three consecutive trials were required, with the points for the project awarded equal to the lowest score earned on the three trials.

Overall, the results showed that even on its first introduction, the students were able to take full advantage of their ownership of the controllers and the flexibility that such an arrangement offered. By the end of the semester-long course, all but one of the twenty-three students enrolled in the course was able to demonstrate a functional controller at the level required to score all 100 points on the assignment. The one student who did not failed to do so for reasons unrelated to the assignment's objectives. Feedback on the quality of the experience was not collected in any formalized or systematic manner from the students. However, evidence in the form of verbal comments from students during classroom exercises, body language, facial expressions and other utterances, anecdotally suggests that the activity was positively received.

## Conclusions & Recommendations

From the perspective of the authors the project was a success. The level of achievement for the students in the course was exceeded, and the inherent strength of direct-observation assessment techniques presents essentially unarguable results: provided the opportunity, the students enrolled in the course were able to successfully design and implement a working controller.

However, the nature of this success should be seen in its context. First of all, in this case, the program was able to benefit from the influx of readily-available electronic components and microcontrollers onto the market. Historically niche items, these have now become almost consumer electronics, with clubs for enthusiasts appearing in many cities. Secondly, the authors were able to offset the additional expense transferred to the students by choosing other course materials—the textbook in particular—in such manner as to contain costs. Due to typically limited student budgets, the ever-present concerns about the rising costs of higher education, and general considerations of fairness, it is recommended that used or re-print texts be used whenever transferring a cost on the order of a college textbook ($100-$200) to the student. For practical purposes the authors chose to order and stock popularly-sold "inventor's kits" featuring most of the electronic components listed in table 1 at the student bookstore. Each student already owned a laptop computer that could be brought to class as was required by institution policy. While not assessed directly, student commitment to the success of the project and careful treatment of the equipment increased relative to previous offerings of the course, possibly due to the use of student-owned equipment. There was only one known case of equipment damage during the semester, and it was for reasons unrelated to the course. In that case the student promptly purchased a replacement part and continued with the course in an otherwise uninterrupted manner.

For institutions wishing to adopt such a component to their programs, it is recommended that the institution ensure that the course be taught in a classroom with AC power receptacles at each student desk. Such an approach was used by the authors to guard against the uncertainties of laptop battery life. An alternative approach is to ensure that the course if offered in an instructional space with sufficient numbers of desktop computers to allow students to work with their microcontrollers in a live classroom setting. Lastly, when connecting the microcontroller to the hardware (servos, sensors, etc.) it is strongly recommended that the microcontrollers be disconnected from the computer and run off a 9V battery to reduce the chance—however unlikely—of damaging the (expensive!) computer from a short or other flaw in the microcontroller and breadboard wiring.

The prototype ball-and-beam demonstrator shown in figures 7 and 8 was built by one of the authors in approximately two hours' time. This construction time is likely shorter than that to be expected of a student due to the experience gained by the author when building the original demonstrator for student use. Allowing for false starts and mistakes, it is estimated that an intrepid student, working alone, should be able to build a similar device in two or three evenings, or about four to six hours of total time. The project was introduced to the students incrementally over the course of the semester, with approximately three weeks allowed at the end of the semester to allow the students to develop their codes and working controllers. During these final three weeks, lectures continued at the normal pace, but nightly homework assignments were shortened slightly to allow students to direct appropriate effort at this project.

The authors also propose that for future offerings of the course, a more comprehensive approach to student feedback should be pursued. Such an approach will confirm if the authors' perceptions of student satisfaction with the project are in fact accurate.

## References


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## Appendix A: Arduino Code for PD controller

```
int servoPin = 9;
int sensorPin = 0;
int DPin = 1;
int posPin = 2;
int KPin = 3;
float sensorValue = 0.00;
float sensorValueold=0.00;
float posSetting=0.00;
float DValue = 0.00;
float KValue=0.00;
int stopTime=0;
int startTime=0;
int pulseTime = 2100;
float poschange=0.00;
float timechange=0.00;
float Pos=0.00;
float Derivative=0.00;
float Kp=1.80;
float Kd=2000.00;
void setup() {
  pinMode(servoPin, OUTPUT);
  pinMode(DPin, INPUT);
  pinMode(sensorPin, INPUT);
  pinMode(posPin, INPUT);
  posSetting=analogRead(posPin)*1.00;
  //sensorValue is something between 0 and 1023//
  sensorValue = analogRead(sensorPin)*1.00;
  //DValue is something between 0 and 1023//
  DValue = analogRead(DPin)*1.00;
  //read in the settling position between 0 and 1023//
  KValue= analogRead(KPin)*1.00;
}
  void loop() {
    startTime = millis();
    //read in the proportional value between 0 and 1023//
    poschange=sensorValue-sensorValueold;
    timechange=startTime-stopTime;
    Derivative=poschange/(float)timechange;
    //set pulseTime between 780 and 2380 uSec//
    //compute pulse time from both position and velocity//
    //DValue is scaling coefficient for Derivative//
    Kp=(KValue/1023.00)*5.00;
    Kd=(DValue/1023.00)*10.00;
    //Kd=0.00;//
  pulseTime = (int)(((posSetting-sensorValue)*Kp+Derivative*Kd))+780;
  if (pulseTime<780){
  pulseTime=780;}
  else if (pulseTime >2380)
  {pulseTime = 2380;}
```

```
  sensorValueold=sensorValue;
  //reduce vibration in system with this loop//
  for(int x=0; x<4;x++)
  {
   digitalWrite(servoPin, HIGH);
   delayMicroseconds(pulseTime);
   digitalWrite(servoPin, LOW);
   delayMicroseconds(25000);
   //reduce noise in signal by averaging//
   sensorValue=analogRead(sensorPin)*1.00+sensorValue;
   posSetting=analogRead(posPin)*1.00+posSetting;
   DValue = analogRead(DPin)*1.00+DValue;
   KValue= analogRead(KPin)*1.00+KValue;
  }
sensorValue=sensorValue/5.00;
posSetting=posSetting/5.00;
DValue=DValue/5.00;
KValue=KValue/5.00;
stopTime=startTime;
}
```