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An Open-Ended Ball-Balancing Laboratory Project for Undergraduates

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***Abstract*— A new laboratory project has been deigned for an introductory course in feedback systems. For this project, kits are provided to students to construct ball-on-beam electromechanical systems with analog control. The students must accurately model the system and design the compensator circuitry. The students are encouraged to rework a variety of elements to improve the system such as: sensor selection and placement, the design of the transmission mechanism, the features (size and mass) of the ball, the power electronics, and the motor drive. These ball-balancing kits provide an open-ended design problem as well as a final product to keep and demonstrate to peers, advertising the course to future students.**

I. Introduction

NEW ball-on-beam projects have been designed for the final laboratory assignment in an introductory feedback course (6.302 Feedback Systems) offered by the Department of Electrical Engineering and Computer Science at the Massachusetts Institute of Technology. In this new project, students analyze a dynamic system and design the analog circuitry that controls the level of a beam with a resting ball. Participating students assemble and modify individual kits to create their own desktop systems with active control. The objective is to provide a challenging design problem that will capture the interest of students and allow for open-ended solutions.

The basic system given to the students is poorly instrumented and lacks a control system. The modifications the students can implement to improve the dynamic performance vary greatly. In this paper, the basic ball-on-beam kit and some key design issues that the students are expected to encounter are described.

II. The Ball-on-Beam Kit

The basic kit consists of a frame made from polycarbonate, a beam made of basswood, a DC motor, and nuts and bolts to assemble the system. The cost of the kits have been minimized to allow students to keep the device at the end of the course. The kit design is straightforward to assemble, and the assembled ball-on-beam system is intentionally uncontrolled. The only output given is the ball position on the beam, which is sensed by measuring the voltage across a resistive material in contact with a conductive ball such as a length of model-train track. This method follows an approach used by Bob Pease in a similar ball-on-beam system [1]. The transmission mechanism to rotate the beam consists of a plastic sector that acts as a gear reducer to decrease the required size of the DC motor driving the plant. The sector is based on a design for a haptic paddle at Stanford [2].

As seen in Figure 1, the assembled device is simple and stylish, so students will want to display it in their rooms and show it to peers. While the basic kit includes all the components necessary to create a working device, students are encouraged to be creative in experimenting with different methods of sensing and actuation and with redesign of the mechanical structure in general. Improvement of the sensing strategy provides a significant design challenge. Additionally, students might prefer to change the gear ratio of the system in order to use a smaller motor, or they may wish to change the beam dimensions, material or assembly.

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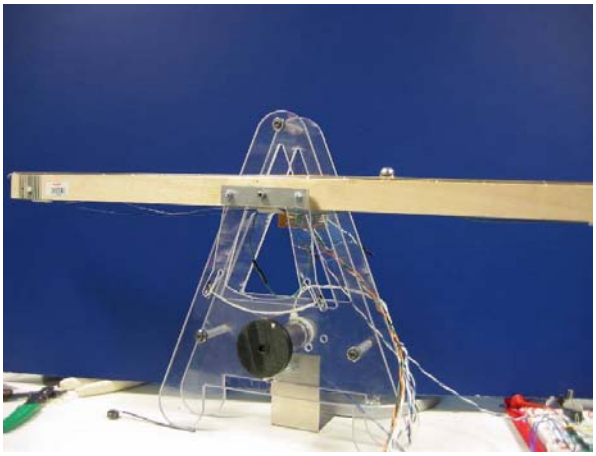

Figure 1. An assembled ball-on-beam kit. The mechanical design provides a sleek, stylish look, and an easy-to-modify structure.

III. MANUFACTURING AND COST

To maintain low cost, materials were chosen for each specific component by considering durability, effectiveness, and cost. Table 1 shows a bill of materials for a set of 50 kits. The total cost per kit is around $20, but does not include fabrication costs. The use of machine shops and labor may vary.

Material	Component	$/unit
Polycarbonate	Frame/sector	9.00
Delrin	Motor pulley	0.40
Bass wood	Beam	2.15
1/4" x 2-1/4" bolts	Bracing	0.60
3/8" Al tube	Bushing	0.33
1/4" Al tube	Beam shaft	0.10
1/4" Nylon bearing	Shaft bearing	0.52
Winchester Drive	DC motor	5.00
1" stainless steel ball	Ball	2.00
TOTAL:	**$20.10**	

Table 1. Bill of Materials. The materials used to produce 50 units of the ball-on-beam kit.

The construction of the kits can be done in most machine shops using a lathe and water jet cutter. Less sophisticated tools are used to complete the manufacturing.

The first step in building the system is cutting the frame (Figure 2) from 1/4" polycarbonate sheets and the sector (Figure 3) from 1/8" polycarbonate sheets. These pieces are cut in the water jet cutter for repeatability, relatively clean cuts, and speed. A sector and two frames can be cut in less than 15 minutes, which costs about $15 for standard maintenance.

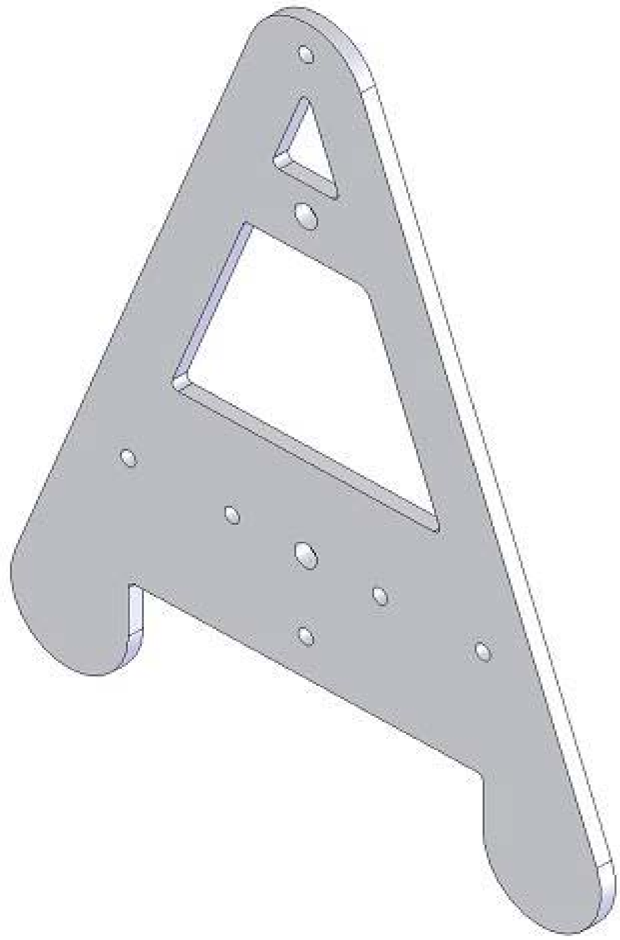

Figure 2. Side frame of ball-on-beam system made from polycarbonate. A part drawing is generated in a CAD program and then machined in the water jet cutter.

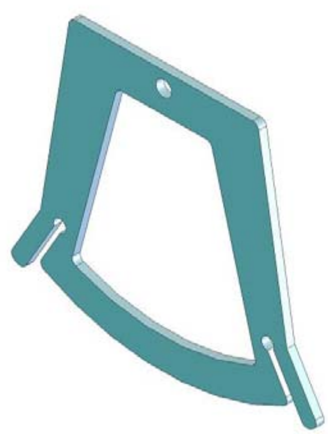

Figure 3. Sector transmission made from polycarbonate that increases gear ratio. Flexures provide preloading. Part drawing is generated in CAD and part machined in the water jet cutter.

The pulley that is attached to the motor shaft is made of 2" diameter Delrin rod. A 3/8" section is cut from the stock and is machined on the lathe. A 1/4" hole is drilled for the motor shaft, and a 1/16" deep groove is cut in the center of the circumference to guide the transmission belt. After using the lathe, a hole is drilled from the outside groove to the center hole to tap a set screw.

Next, the beam is constructed using 2-foot-long bass wood pieces. Once a beam that will support the conductive rail sensor is assembled, the center hole can be drilled, the 1/4" shaft inserted, and the sector attached.

Finally, the set-up is fully assembled as seen in Figure 4. The beam shaft rests in the nylon bearings that are inserted in guide holes in the frame, and a 3/8" aluminum tube is used as a bushing to separate the frames and allow the beam to rest within the structure. To attach the motor pulley to the gear sector, dental floss is wrapped around the motor pulley and tied to the sector.

Figure 4. Assembled ball-on-beam system. The components are put together in several, easy, straightforward steps to give an elegant appearance and effective apparatus.

IV. Lab Project

Students intentionally received a device that was both badly instrumented and uncompensated. Two of the key issues that students were expected to analyze included sensor performance and compensator design. The project is open-ended, however, and students were also encouraged to explore other methods of improvement, which may include modifications to the ball or to the transmission mechanism that supports it. One team of students decided to redesign the set-up and build their own from scratch (Figure 5). Their efforts were well spent and significantly improved the system performance.

Students found two very separate main challenges that needed to be solved. First, a servomotor loop needed to be designed to control the beam angle. This minor-loop system required a high bandwidth to reduce the phase delay of the ball position major-loop system and good disturbance rejection to minimize the effect of the torque exerted by the ball. Once the minor-loop servo was developed, the ball position loop needed to be closed, and appropriate compensation needed to be designed.

In addition to solving the control-loop design problems, both of the feedback loops required additional sensors. The servo loop required a tilt senor and the ball loop required a position sensor. All students decided to replace the train track with a more resistive sensor design. As an alternative to having a single element of wire spanning the length of the beam as the sensor, some students opted to wind a dowel with small-gauge nichrome wire (Figure 6). This strategy increased the length of the wire and its resistance, which gave the sensor more resolution. The tightly wound coils also seemed to reduce the contact surface of the wire to the ball, which may have improved the contact resistance by increasing the contact pressure.

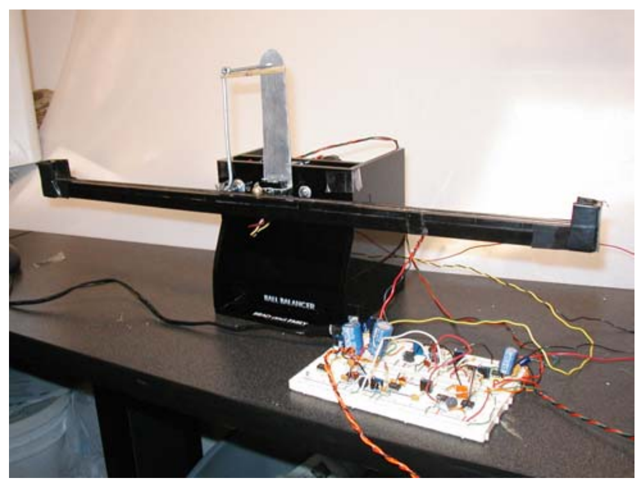

Figure 5. Students designed this apparatus and built it from scratch.

Along with modifying the ball position sensor, students also explored the beam angle sensor. For this particular offering of the course, Analog Devices donated several ADXL202 accelerometers. One group decided to incorporate this device while others used a potentiometer attached to the beam shaft as in Figure 7.

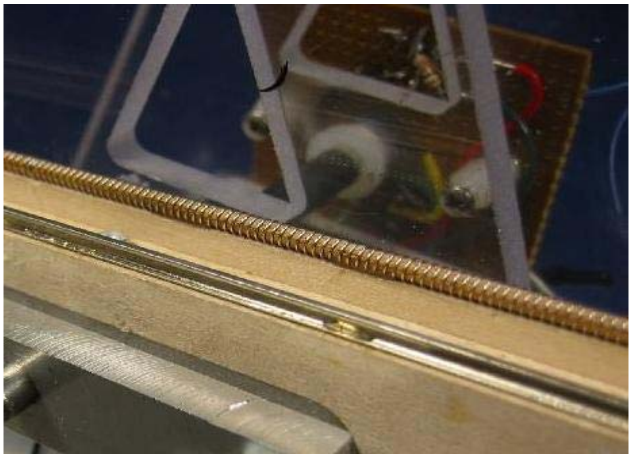

Figure 6. Nichrome wire tightly wound around a dowel. This method of sensing was more successful than a single wire because it provided more resolution with limited current.

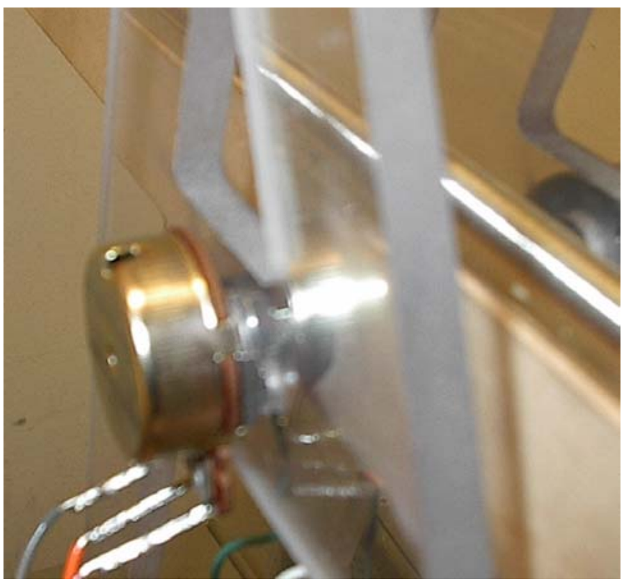

Figure 7. Potentiometer on shaft. In this modification, a potentiometer was attached to the shaft of the beam to determine the angle at which the beam slanted.

V. Sensor Issues

In the basic kit, students are provided with a feedback sensor for ball position that is essentially a linear potentiometer. The design provides a linear voltage distribution across one resistive rail and detects the voltage output on the other. Students are offered a number of materials for the resistive rail, including N-gauge model train track, steel welding rod, or small gauge nickel-chromium wire. All of these choices transmit a usable, but suboptimal, feedback signal.

The problems lie in the total resistance of the track and the contact between the resistive rail and the conductive ball. A low total resistance of the track requires high currents and produces low voltages for sensing. The total resistance of the model-train track is 0.2 ohm, thus requiring a large bias current (1 amp), and only producing an end-to-end output voltage variation of 200 mV. In addition, a combination of low contact pressure, high contact resistance, and partial oxidation causes intermittent signal generation. However, proper buffering and filtering can improve the signal significantly to produce an acceptable feedback signal.

Several sensor alternatives have been explored:

1. A linear potentiometer constructed from model-train track, steel welding rod, or small gauge nickel-chromium wire. A three-ohm length of nichrome wire was used by the students in Figure 5, with a bias current of 0.5 amp.

2. A linear potentiometer constructed from small gauge nickel-chromium wire wrapped around a wooden dowel as shown in Figure 6. This strategy increased the length of the wire and its total resistance to about 200 ohms, which gave the sensor more resolution with less current.

3. A linear potentiometer constructed of 26 gauge nickel-chromium wire wrapped around a 10-32 nylon threaded rod. The threaded rod allows the wire to be tightly wrapped while keeping each turn electrically isolated from the next.

4. A linear potentiometer constructed from conductive plastic. With a resistance of about 5×10^4 ohms/square, high resolution is possible without requiring high amperage, but the contact conductivity of this specific plastic is low, and scratches to the plastic surface affects the signal quality. A 4x8 roll of conductive polyolefin (Contrim VF®) was purchased from Westlake Plastics for testing purposes, but contact between the plastic and the ball is not reliable.

5. An ultrasonic transducer promises to be a high-resolution but expensive option. Also, the field of view may be too wide. These transducers are available with resolutions as good as 0.1%, but cost $60 each, even in quantity.

6. Infrared range finders have high resolution, but with a narrow field of view, and are more cost effective. Models are available that are accurate up to 2 feet.

7. One student team proposed, but did not complete, an inductive loop sensor that senses the position of the ball using the mutual inductance between two coils in the horizontal plane. As the ball moves along the beam, it reduces the effective area of one of the loops.

VI. Student Experiences

Students found the lab challenging in many aspects. Although most students felt that the compensator design was the main focus of the project, it was overshadowed by sensor issues. A common holdup that was mentioned was the functionality of the ball position sensor. The consensus was that the ball position sensor was the most critical component and also the most difficult to overcome. The quality of signal from this feedback element dictated the smoothness of the response. A significant amount of student time was spent trying to solve this problem resulting with device performance ranging from marginal to quite functional.

Of the four teams of students that completed the project in the fall of 2003, there were varying degrees of success, but all came away with something to show and lessons learned. Overall, student reviews of the project assignment were positive. Students were excited about the prospect of building a system and watching their controller perform on a real plant rather than reading a scope. The joy of witnessing the system work was also rewarding. Some students described the assignment as a "very cool project."

VII. Conclusion

Students have recently been offered an open-ended feedback design project in which they were asked to control a ball-balancing apparatus. The kits that were provided offered a jumping-off point to create really nifty, working ball balancers. Also, the knowledge students gained through this course and other courses helped them employ a variety of modifications, all with the goal of improving the dynamic performance of the ball-on-beam system.

VIII. Acknowledgments

Thanks to Analog Devices for donating ADXL202 accelerometers. Thanks to the students who participated in this trial run of the project assignment for their efforts and for providing constructive feedback. Thanks to Emily Fox, Bennett Ito, Bradley Kaanta, Brandon Kam, Hongshen Ma, and Andrew Valiente for providing some of the photos in this paper. Special thanks to Professor David Trumper for supplying the DC motors used in the kits.

References

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