AC 2008-2182: DECISION-MAKING IN THE DESIGN-BUILD PROCESS AMONG FIRST-YEAR ENGINEERING STUDENTS

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Decision-Making in the Design-Build Process among First-Year Engineering Students

Abstract

Students in a first-year engineering program at The Ohio State University are required to complete a quarter-long course which incorporates a team-based, design-build final project. Design skills among first-year students are often found to be rudimentary, and teaching the skills necessary for students to successfully complete a design-build project remains a constant challenge. The final project requires the design and construction of a functional roller coaster model using material from a custom-made kit provided to the students. Key components of the project are: initial design, analysis and revision, initial construction and testing, design changes (to correct defects and meet performance requirements), final design, and measurement and performance analysis. The teams submit preliminary designs as 2D drawings, with the option to use 3D CAD software (Autodesk Inventor 2008©). They then develop initial energy models of their coasters using Excel, use their results to find design problems, and revise their design. Once they have approved revisions, they begin to build their coasters. Upon completing the coaster requirements, students document their final design, including a revised Excel energy model. In order to validate their designs, students use eight custom-made speed sensors that they attach to the coaster track to measure the speed of the coaster car at critical locations along the track. Speed measurements are captured in LabVIEW, analyzed, and submitted in a final report as evidence of how well the Excel design model reflected the actual behavior of the roller coaster. The project culminates with competitions among teams, concluding with an oral presentation by each team on lessons learned and recommended design and construction improvements. This paper emphasizes how students who have little or no prior engineering experience conceptualize and represent a complex design problem and how they use both theoretical models and actual test data to make informed design decisions.

Introduction

In 2001, the College of Engineering at The Ohio State University introduced significant changes into the curriculum for all first-year engineering students, with the addition of hands-on laboratory projects and team-based design and build projects[1,2]. The motivations for doing so at the first-year level were threefold: (1) to achieve significant improvement in the year-to-year retention rate of engineering students, especially through graduation, (2) to expose students early to realistic engineering projects containing elements of uncertainty, risk, and many acceptable solutions, and (3) to cultivate teamwork, project management, creative thinking and effective communication skills.

While certain aspects of improvement are difficult to quantify, the first-year program has been successful in all three areas, aided by higher admission standards, direct enrollment to the College, and improved advising strategies. For example, 86% of the Autumn 2006 first-quarter

Engineering freshmen at Ohio State returned as Engineering students for Autumn 2007 (compared to 92.4% for all majors and the national average of 77%, all majors). Anecdotally, faculty teaching upper level courses report that students who have completed the first-year sequence are highly motivated, excited about engineering as a career, and better equipped to attack the challenges of upper-level courses.

The first-year engineering program at The Ohio State University consists of two tracks, taken by all first-year students: a standard track and an honors track, with approximately 75% of students in the standard track. The standard track consists of two courses totaling six quarter-hours credit, and the honors track, three courses totaling twelve quarter-hours credit. Both tracks include traditional freshman engineering course components, including graphics, 3D CAD (Inventor 2008), and computer programming, but are augmented with hands-on engineering laboratories (covering subjects in many engineering disciplines) and conclude with a final design and build project. Students in each course work in four person teams. Professional communication and teamwork skills are emphasized through team-based report writing and oral presentations. The team-based, hands-on portions of the courses amount to approximately 40% of the student's final grade.

For the design and build project, honors students are required to design, build, and program an autonomous robot. The robots contain a microprocessor, motors, gears, wheels, actuators, sensors and other standard and custom parts that the students assemble, mostly from scratch. The autonomous robot is required to perform a task—such as move containers around a model warehouse structure, or clean up a simulated chemical spill. At the end of the course, students enter their robots in a final competition, held in the basketball arena, that is well-attended by friends, family, and faculty, to compete for prizes and well-deserved bragging rights.

Standard track first-year students are required to design and build a functioning model roller coaster. The roller coaster design/build project, first introduced in 2004[3], is now in its fifth academic year, with approximately 800 students per year having completed the project. Students are given a standard-issue kit of parts and have eight weeks to design and build their coasters, with four sessions devoted to testing and design changes, until the coasters meet a minimum set of performance specifications.

From its inception, one of the deficiencies the roller coaster project had was the lack of an accurate coaster speed measuring technology that was inexpensive enough to use on coasters at multiple track locations. Inexpensive speed sensors were developed by program faculty and staff and added to the roller coaster kits in 2006-2007. Using the new speed sensors, students now are able to (1) measure coaster speeds accurately at multiple locations along the coaster track, (2) build more accurate energy models for their coasters, and (3) predict and verify the effect of design changes on coaster behavior and performance. This paper presents the recent improvements in the roller coaster design/build project and how they have affected the decision making processes of engineering students in the first-year engineering program at The Ohio State University.

Roller Coaster Project Description

Figure 1. Typical roller coaster construction.

A detailed description of the original roller coaster design-build project was published in 2005[4]. By that time, the coaster project was mature and had become popular with students and faculty alike. It clearly had significant educational value and relatively consistent outcomes, even though the "engineers" running the project were first-year students, typically with little or no prior engineering or project management experience.

The roller coaster is a simple gravity-driven, open-loop system, with a typical coaster shown in Figure 1. The track rails consist of two parallel lengths (25' long) of ¼" O.D. polyethylene tubing. The track is held in place by small nylon snap-fits placed every few inches along the track. The snap-fits maintain constant distance between the rails and connect the track to the support structure. The support structure is assembled from various lengths of ½" plastic pipe tubing and pipe fittings. The coaster ball is a 1.0" diameter nylon sphere that rolls between the track rails. Each coaster kit consists of over 500 individual parts.

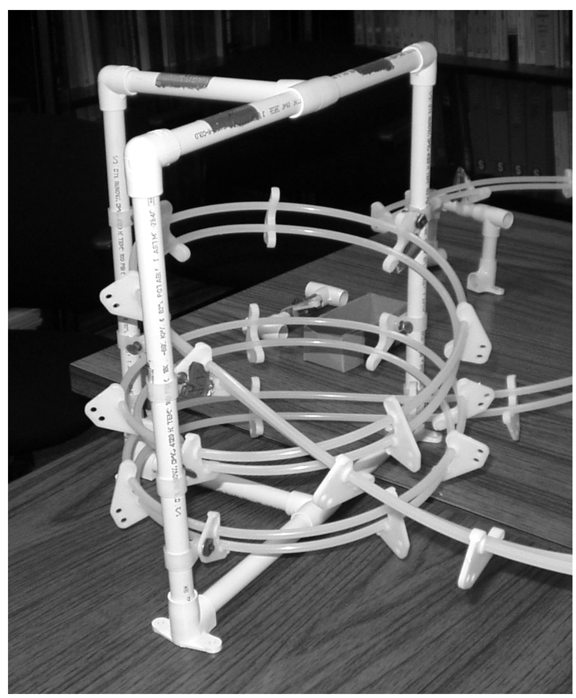

Figure 2. Details of track construction.

The wooden starting tower, also shown in Figure 1, supports the track at the beginning, where the starting point is located. The student in the middle is about to release the coaster ball for a coaster test run. Additional details of track construction, the snap-fit connections, and support structure are shown in Figure 2.

Design and Performance Requirements

The footprint of the coaster must fit within an area of 4' x 5', slightly smaller than the laboratory table space assigned to each team.

In order to receive a minimum acceptable score, the coaster must include the following features:

- A single vertical loop
- A single horizontal loop
- A simple bump
- A section of horizontal straight track

A successful coaster design with just the minimum features receives a score of 84%. Extra features added successfully result in extra points in the final project score (to a maximum score for a successful coaster of 105%). Any number of extra features may be added (without exceeding the 25' overall length restriction). Some of the popular extra features attempted for extra credit have been:

- Double vertical loop
- Upward horizontal loop
- Double horizontal loop (downward or upward)
- Figure eight
- Triple loops (both vertical and horizontal, very difficult)
- Other exotic geometries (such as a cobra roll or batwing)

Figure 3 shows a roller coaster design submitted by students as an Inventor assembly drawing. A complete set of models of the parts in the coaster kit is provided to the students to use to design their coasters in Inventor.

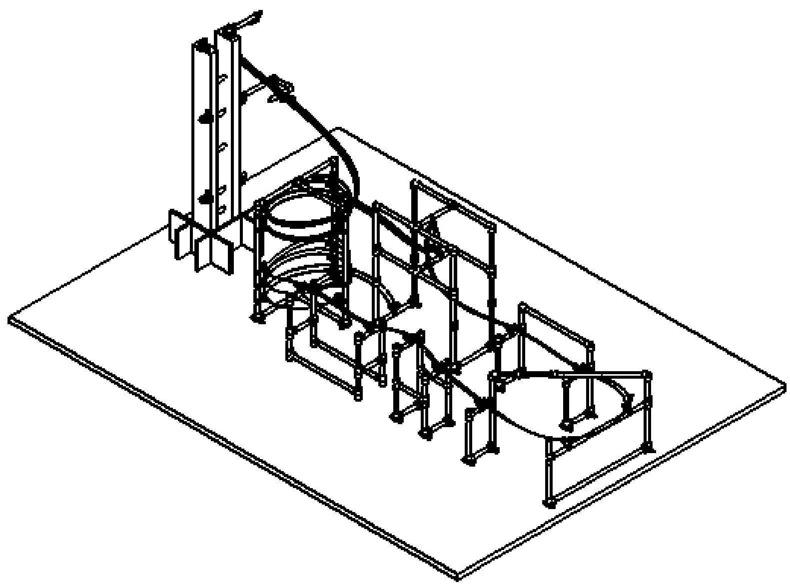

Figure 3. Roller coaster design drawing in Inventor.

The scoring model plus large number of design and execution possibilities encourages creativity and risk taking.

Project Challenges

A successful coaster is one in which the coaster ball starts at the release point, races along the track, and reaches the end of the track without falling off. During final tests, the coaster must run perfectly at least three times in a row.

The primary challenge for students is they have eight weeks (each lab meets two hours per week) to design and build a coaster that works consistently. Coasters with marginal design or construction characteristics might run properly several times in a row, and then stop running altogether. Small changes in track geometry can cause considerable changes in coaster behavior. A further complication is that the coaster must be torn down at the end of each laboratory session and then rebuilt at the beginning of the next session. Mechanical skills and insights vary markedly among individual students.

In vertical loops, if the speed is too low, the coaster ball falls out of the top of the loop. The solution is to either decrease the loop radius or increase the speed of the coaster ball at the entrance to the loop. However, changes made to any feature will change the dynamics of all successive features.

In horizontal loops, the coaster ball speed and the track bank angle must be carefully controlled. If the coaster ball goes too fast and the bank angle is too low, the ball flies over the top of the track. If the speed is too low, or bank angle too high, the ball drops off the low side of the track.

Most student teams have considerable difficulty translating initial coaster designs into fully functional coasters. Students find it difficult to determine why it does not work, primarily because there are multiple failure modes at work. Students find it difficult to formulate an effective strategy to fix the coaster, primarily because of the complexity and subtlety of the system.

The reasons for these challenges are numerous. The potential energy of the rolling sphere (coaster car) turns into kinetic energy and back to potential energy as it moves along the track. Total mechanical energy (the sum of potential and kinetic energy) is generally decreasing, however, as the ball moves down the track due to friction, air resistance, and other causes. The potential energy at the beginning represents an energy budget that must be preserved as much as possible to make sure the ball makes it all the way through the coaster. Early in the quarter, students perform experiments to estimate the coefficient of rolling friction, the energy losses in vertical loops, and the approximate angle at which the ball will start sliding as well as rolling. This last is important because sliding friction is much higher than rolling friction. They then use these results plus an estimate of air resistance to estimate the speed of the ball at key points in their initial coaster design using an Excel spreadsheet. This initial model is used to look for design problems, such as not having enough speed to reach the top of a vertical loop, flying off the track at a bump, or having excessively high speeds in a horizontal turn. Students must come up with a plan to revise their coaster design to fix these issues before they are allowed to build.

The design spreadsheet only includes estimates of energy losses that are easy to calculate and students learn quickly that the coaster system is far from ideal as they begin to explore and understand the second-order effects that come into play:

- Energy loss due to the ball slipping on the track at high track angles (hard to estimate when the ball is both sliding and rolling)
- Energy loss due to deformation of the track caused by rolling forces (when the track is poorly supported)
- Energy loss due to induced motion of the support structure
- Extra energy lost in high speed horizontal turns (the force to make the ball turn is largely supplied by the upper track)
- Generally poor track conditions introduced by multiple build cycles.

In short, coaster performance exhibits far-from-ideal behavior—perhaps the student's first introduction to real-world engineering systems—for which physics is only approximate, and judgment, insights, and experience become important.

Because of the uncertainties involved, after their initial set of revisions, students tend to take a "cut and try" approach to repairing coaster features that do not work—tweak this, tweak that, and see what happens. After adjusting one feature to make it work, students discover they have caused the next feature to fail. In many cases, after the students have properly adjusted each feature, usually one feature at a time from start to finish, the result is a coaster that works properly, but does not remotely resemble their initial design. In this case, the “cut and try” strategy rarely works very well.

New Speed Sensors

The new speed sensor, which was developed by program faculty and staff specifically to improve the outcome of the roller coaster project, is shown on a section of track in Figure 4. Each team is supplied with eight sensors to use on their coaster.

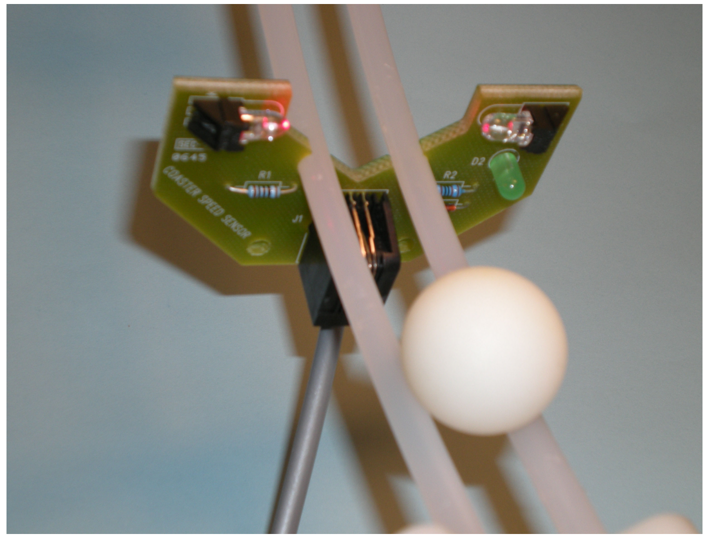

Figure 4. Roller coaster speed sensor.

The speed sensor was designed so students can easily clip it to the track at critical locations. In Figure 4, a coaster ball is shown approaching the speed sensor. The circuit board shown has a red LED at the top left, opposed by a phototransistor at the top right, creating an optical path above the coaster track, on a line through the center of the coaster ball.

When the coaster ball arrives at the sensor, its leading edge interrupts the light beam between the LED and the phototransistor, causing the circuit to produce a positive pulse output. After the trailing edge of the coaster ball exits the sensor, the pulse falls to zero. The width of the sensor output pulse is inversely proportional to the speed of the coaster ball.

The pulses from the eight speed sensors are routed to a central connector board and, from there, to a data acquisition card installed in a PC at each lab bench. A LabVIEW application running on the PC collects speed sensor data from all eight speed sensors during each test run and displays the following information:

- The pulse width recorded at each sensor
- The speed measured at each sensor,
- The transit time between sensors

The LabVIEW display window is shown in Figure 5. The LabVIEW application also lets students save the data to a file on the PC.

The speed sensors are relatively inexpensive and have proved to be remarkably rugged and easy to use. Testing has shown that the sensors measure speed with accuracy on the order of 3%.

Figure 5. LabVIEW application that collects pulse width data and calculates speeds for all eight speed sensors.

Students are provided with the speed sensors during their first build session. This allows them to compare speeds with their design calculations and help make informed decisions about how design changes might be expected to affect later, as yet un-built features. At the end, students are required to document their final design and re-run the design spreadsheet. They then instrument their coaster and use the measurements to analyze where and why their final design behaves differently than the design spreadsheet predicted. For their analysis, students compare measured with predicted speeds. Where the two curves diverge, there has been some energy loss not represented in the Excel model.

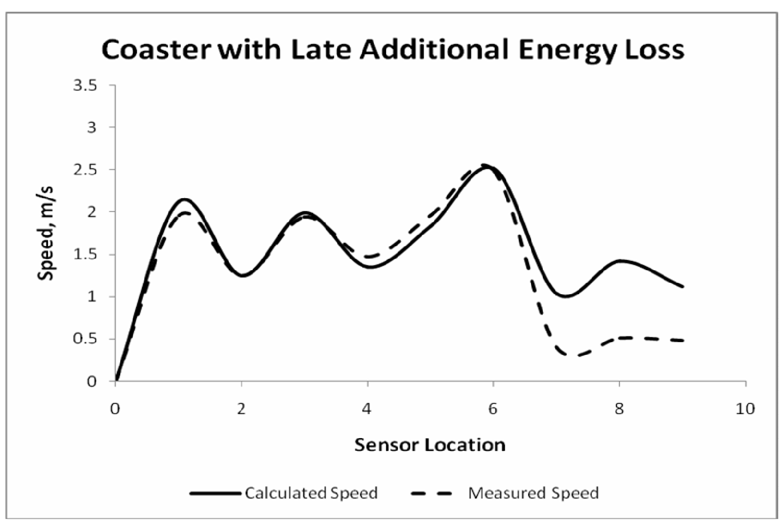

Figure 6. Comparison of measured and predicted speed for an example student coaster design.

Figures 6 and 7 show examples of measured vs. estimated speed at different locations along the coaster track for two student designs. Figure 6 shows a case where significant additional energy is lost only after a number of features. This team spent a lot of time on the early part of their coaster and did a good job of minimizing energy losses. The beginning of the coaster design consisted of an initial drop to gain speed, followed by consecutive separate vertical loops. After this, the track dropped again to gain more speed and entered a double upward horizontal loop before a twisting downward feature, bump and the end of the track. Up until sensor 6, placed at the entry to the double horizontal loop, the energy loss is well explained by rolling friction, air resistance, and the increased rolling friction caused by g-forces. Additional energy was lost, however, in the double upward loop. This is because of the difficulty of modeling high-speed horizontal turns due to g-forces coupled with varying track support and geometry.

By contrast, Figure 7 shows a similar speed comparison for the student coaster design shown in Figure 1. Here the design had a significant additional energy loss during their initial drop. Part of this was likely due to the ball sliding as well as rolling during the steep initial drop and part due to the relatively sharp bend at the bottom of the initial drop. After that point, the calculated and measured values track each other fairly well. There are only limited additional energy losses in the rest of their coaster. In this case, the students decided to both accept and design around the initial energy loss because they wanted the "thrill" of the initial drop and pull out from the drop. They had to redesign parts of the rest of their coaster because of the reduced energy available.

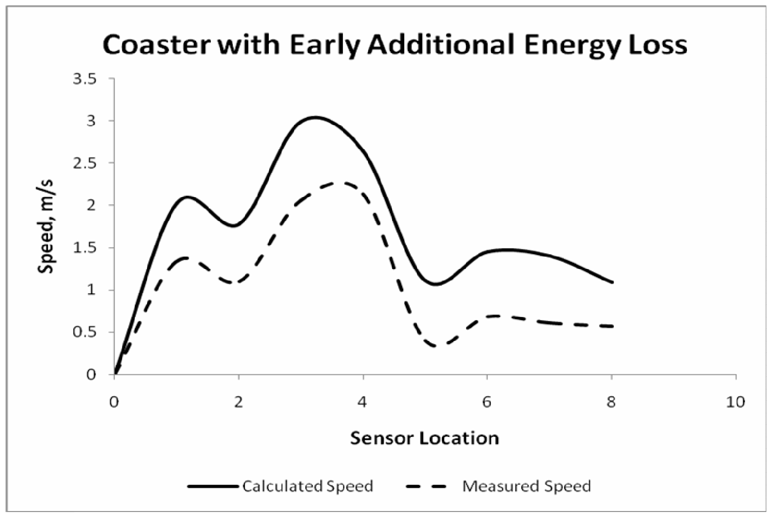

Figure 7. Comparison of measured and predicted speed for the coaster design of Figure 1.

Both designs are relatively good designs. They lost additional energy in expected ways, one in a high speed horizontal curve and the other in an excessively steep initial drop. Poor designs, however, lose excessive energy in features where it would not be expected, and measurements aid in locating these problems.

Assessment

Student performance is assessed at numerous points during the quarter. From the beginning of the quarter, students are required to keep a project notebook that details brainstorming ideas, group meeting notes, a project schedule, design drawings with calculations, a paper trail of all design modifications, and the final design with calculations. The project notebook is checked weekly during the quarter. Students submit initial paper design documentation, which includes a quality drawing of their initial design, a summary of modeling results based on the design, and student answers to design evaluation questions. Each coaster undergoes a final performance test (while instrumented with speed sensors) and must run successfully three straight times for full credit. Students then write a final report documenting the entire project, including an analysis of the speed measurements taken from their performance test. Each team gives an eight minute oral presentation discussing the development and performance of their coasters. Lastly, on the final exam for the course, students are asked questions about coaster dynamics.

Conclusion

The new speed sensors have added an extra dimension to the roller coaster design and build project at The Ohio State University. They now allow precise measurements of roller coaster dynamics at critical locations, enabling students to:

- Analyze failure conditions at each feature
- Predict and verify the effects of design changes
- Build and verify an accurate energy model of the entire coaster system
- Analyze and discuss energy losses, i.e. where and why energy losses are greater than expected from friction and air resistance alone.

The sensors have become a useful tool in teaching teams of first-year engineering students how to design, build, and analyze a complex engineering system.

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