A Simple Digital Logic Project for Freshman Engineering

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Abstract

Like many other schools, Polytechnic University has developed robotics projects using commercial products such as Robolab[®] for its Freshman Engineering course. These projects have been well-received by many students[1]. However, some Freshman students have commented that they wanted something more related to Electrical Engineering and Computer Engineering.

To meet this demand, we have developed a project for digital logic design that uses a model train set. The project uses a train layout with several express and local tracks, with paths blocked with freight cars. The student uses sensor inputs from the layout to determine which track sections are occupied, and to find a path for a locomotive to follow from one end of the layout to the other. Digital logic is used to find the path, and to actually throw train switches to have the locomotive follow the proper route.

Students are familiar with model trains, and actually driving the switches with the logic they design captures their interest. The basics of simple logic design can be covered quickly and implemented using LabVIEW[®] without getting into circuit analysis. The track layout that is employed provides a challenge in finding the optimal route, but at the same time is not overwhelming to the student. It can also be the basis for a lively design competition.

Background

As part of its membership in the NSF Gateway Coalition, Polytechnic devised an "Introduction to Engineering" course required of all students in the Freshman year, with most students taking the course in the first term. The charter of the course is to provide a "hands on" approach to engineering to complement the theory they are learning in their other courses, and also to give the students a better idea of what engineering is. A major component of this course is a term-long design project. Early in the term, the student is presented with a range of options for projects including the design of a house, several robotics projects using Robolab and, more recently, a project in digital logic design. This project was added due to requests from students to have a project involving Electrical Engineering or Computer Engineering. The student must choose a project by the third week of the term, which means that students usually pick projects based on personal interests rather than technical expertise. In addition, typically they will not be seeing courses in their majors (e.g. "Introduction to Logic Design") until much later, meaning that they have little theoretical background to apply to the project. It has also been our experience that these students are really making a transition to college at this point, so the project has to have a "fun" content in order to keep the student enthusiastic and hold their attention. In order for them to gain an idea of what engineering is, the project should also allow different technical

approaches and solutions so that the student gains an appreciation of the tradeoffs an engineer has to make.

For a number of years, designing a house, including utilities and lighting, was the project used. Although some students enjoyed the project, many students felt it had limited application to the specific field of engineering that they liked. Also, it did not have enough excitement. Reacting to these feelings, we added additional projects to the course involving Robolab. These projects certainly increased the excitement of the students as the robots had to traverse mazes and pick things up, but the attitude of many students is that these projects were too closely tied to Mechanical Engineering. The Electrical Engineering and Computer Engineering students were particularly vocal about this, where they wanted a project that was as much fun as the robots, but involved some aspect of electronic design.

As a result of these comments, we reviewed what good characteristics the existing projects had, and how they could be adapted to an EE/CompE project. Several characteristics were found:

- It had to involve motion. Seeing their work actually do something captivated the students.

- It had to have a wide range of possible solutions. Students found projects that were overly structured to be boring.

- It had to involve a minimum of background knowledge. Projects that required significant gathering of background material were overwhelming to students already carrying a heavy course load and probably facing time management problems for the first time. If possible, most if not all the background knowledge had to be covered in one of the course labs.

- It had to be hard to have a total failure. Such failures are extremely discouraging to a new engineering student. On the other hand, even a partial victory had some measure of reward. As new engineering students, it was important to keep their interest and enthusiasm.

- It had to have some sort of competition. For the Robolab projects, it was easy to have scoring systems based on time or difficulty of tasks.

With these characteristics in mind, we began to consider projects. Also, our Freshman Engineering course has heavy participation of upperclassmen as mentors, so we solicited their input as well.

As a parallel activity, some of the Freshman Engineering mentors were building a model train set to put in one of the building lobbies during the Winter holidays. This project attracted considerable interest, with many of the participants having no prior background in model railroading. One aspect of this was a fully automatic interlock system that controlled the trains to avoid collisions and also control speed. Like many projects of this type, it quickly became enmeshed in "feature creep", and is still a work in progress. However, there was no question that it engendered great enthusiasm, including some Freshmen.

At this point, some of the students involved in the model train project felt that something involving model railroading could be adapted to become a Freshman Engineering project. The

technical background they had gained in using digital electronics to control power to the trains also appeared to be an asset. Further refinement led to the conclusion that something involving digital logic would be most effective since the students could use LabVIEW for the project, and there was an existing lab in the syllabus that taught the fundamentals of digital logic using LabVIEW.

At this point ideas came quickly, and centered on a section of a railroad or subway involving express and local tracks, where a train would be at one end and had to get to the other by finding a route around sections of track that were blocked by other trains. Using this as the starting point, we began design. Almost immediately, physical space became a major concern. Our labs are not huge, and having train tracks running the lengths of rooms was not an option. In addition, there were concerns about storage and how to avoid damage to the project. As a result, we scaled down the project to the point where we took a single four foot by eight foot sheet of plywood and cut it in half, leading to our first design constraint: length of track. This led to the next step where entire trains were replaced by single railroad cars. Given all this, a candidate track layout using HO gauge model railroad stock was designed, and is shown in Figure 1 below.
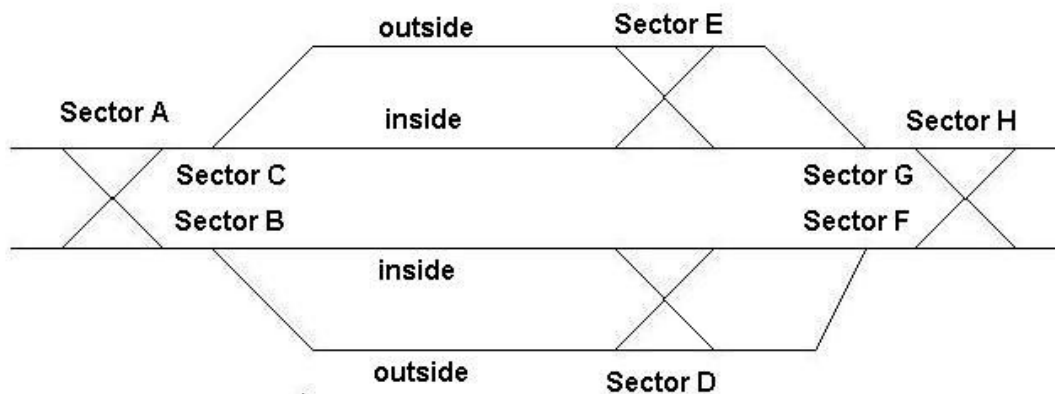

Figure 1: Track Layout

The initial mission statement was that a locomotive would be at the left end of the tracks, and train cars would be positioned on a random selection of sections of track for each of the sectors. The locomotive then had to find a path, if one existed, to get the locomotive to the extreme right end of the tracks.

To achieve this mission, we had to design a testbed that the students could use. This testbed would have to supply information on the location of the locomotive and the train cars, specifically which sections of track were occupied and which ones were not. The students would then write a LabVIEW virtual instrument program that would take these inputs, find a solution, and send output signals to the testbed. Interface electronics under the testbed surface would arrange the track switches to have the locomotive negotiate the route to the other end. If no path was possible, the virtual instrument should light an error light on the LabVIEW "front panel" if no path existed.

This led to a number of tasks that had to be completed by the Freshman Engineering staff. The first was making the status of sections of track available to the student. This was done in two stages. The first was mounting a system of photocells throughout the testbed. Our belief was that if the section was occupied that the car would block light to the photocell, and that if the section was open, ambient light would be sufficient to provide a threshold to show the section as unoccupied. We buried the photocells in the track bed, and began testing. We encountered a number of problems where enough light would leak in from the sides of the cars to still trigger the photocells. Also, ambient light levels in the lab varied greatly during the day, making threshold values change significantly. Even redesigning how we buried the photocells did not solve the problem, so we ultimately made the decision to feed analog voltages to the LabVIEW Data Acquisition and Control (DAC) card, and allow a person in charge of testbed setup to dynamically adjust the thresholds using sliders in a LabVIEW Virtual Instrument® (VI) until the system operated properly. This takes about five minutes.
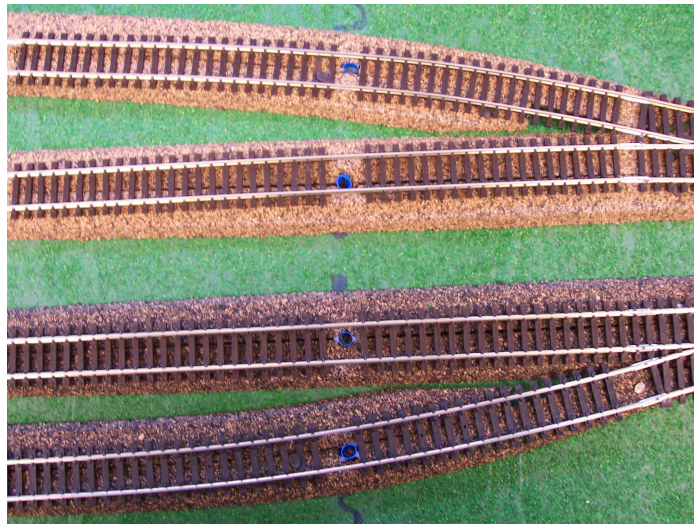

Figure 2: Photograph of photocells in track bed

The next issue was how to present the occupancy data to the students' programs. This was done using a LabVIEW VI that gave the students a string of Boolean values for the occupancies. A value of 1 ("true") indicated that a section was occupied, and a value of 0 ("false") indicated it was not.
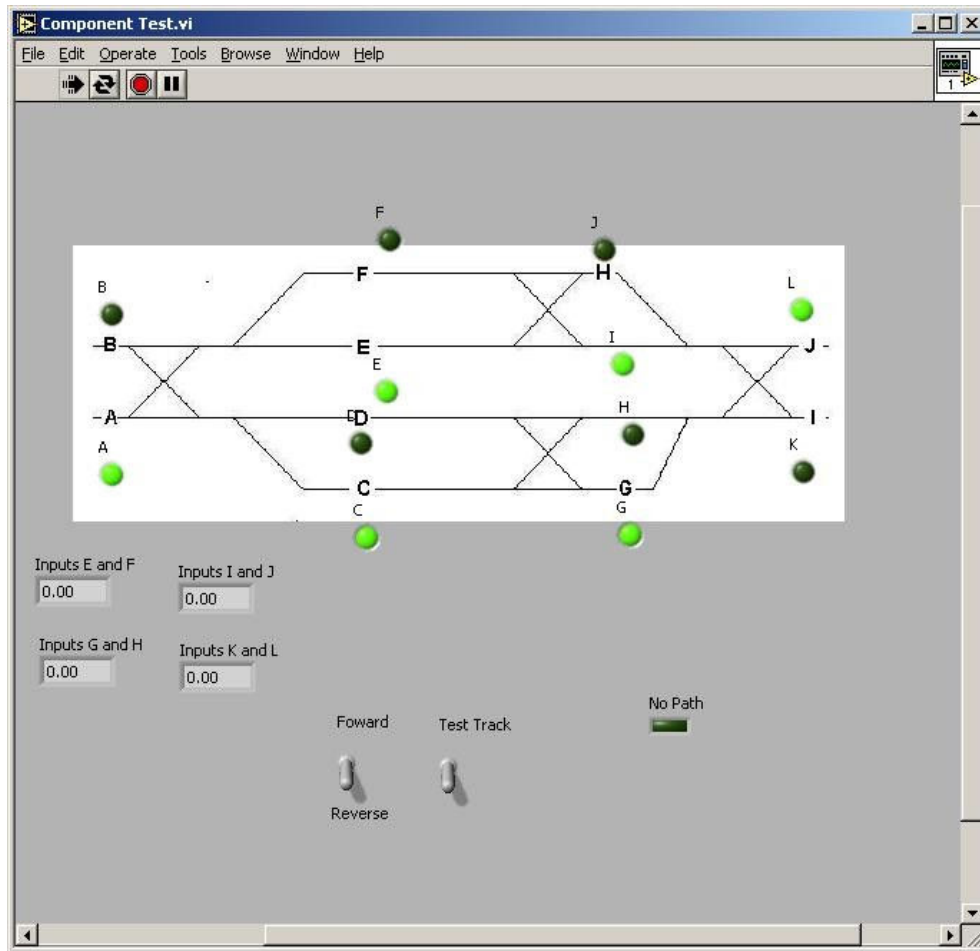
Figure 3: LabVIEW VI showing track occupancy

The next step would be the responsibility of the students. Their project was to take this string of data and create a Boolean string indicating how the track switches should be thrown, with a 0 indicating the corresponding track switch should be straight and a 1 indicating it should be turned. This was the heart of the project, where the students had to create one or more Karnaugh maps and corresponding logic reduction to produce the proper output values for the inputs presented. Although it is possible to do this with one huge Karnaugh map, it is also possible to partition the problem to make it more tractable. This Boolean string would then be sent to a LabVIEW VI that controlled the switches.

At this point the VI sent the output signals back out through the DAC board. This presented a problem since the power levels supplied by the DAC board were not sufficient to drive the track switches. This was solved by using triacs that were driven by signals from the DAC board, with the outputs of the triacs driving the track switches. This combination of digital logic driving power electronics proved to be a significant challenge, but the team eventually overcame it.

Our initial solution had all the track switches thrown to their proper position simultaneously. This led to problems with power surges and circuit overloading, plus the only phenomenon actually seen or heard was a loud "click" as the switches were positioned. To ease both problems

we redesigned the VI that threw the track switches to do them sequentially. This leveled out the power requirements, and also made the activity much more interesting since students could now see their solution "rippling" down the tracks. We then worked on how quickly to sequence the switches and found that 100mS for each stage was more than sufficient to throw the track switch, but also made the "rippling" phenomenon interesting to watch.

Once the track switches had been thrown, the person in charge of the testbed would then check to see if the locomotive could run from one end of the testbed to the other. If so, they then actually had the locomotive navigate the path to verify that it worked, and also to provide visual feedback to the students that their solution worked.

At this point the cars blocking sections of track were rearranged, and the student's program provided by the solutions had to reread the inputs and find a new solution for the locomotive to get home again. As before, once the students had a solution, the track switches were thrown and the locomotive was driven back to the end where it started.

Project Introduction

Since this project was fairly sophisticated, we believed we should have an "alpha test" before full scale deployment, limited to two teams of students of two people each. This allowed us to check out the documentation and circuitry in a "real world" environment, but still provided a limited amount of competition to the two teams of students. This approach worked well, with the students providing feedback on things they found confusing or unreliable. Two problems that were particularly challenging were the photocells buried in the track bed, and electrical power management.

Looking at the specification sheets, it appeared that the photocells had a wide range of resistance, making it easy to get a threshold between light and dark. However, when we actually started using the cells we found that the range was far from linear, and that the photocells showed little directivity, even though they were fitted with lenses during manufacture. As stated above, this problem was eventually solved through LabVIEW, but we are still not totally satisfied with the solution and will probably revisit this issue in the future.

The track switches are driven by solenoids, and we found that the solenoids draw significant power while they are in use. Since the testbed does not have any feedback showing the switch positions, and sometimes the switches were (unnecessarily) moved by hand, we had to supply power to all the solenoids to insure that the track switches were in the proper position. We considered adding a feedback capability to tell us the track switch position, but rejected this approach for several reasons:

- We had to have power capacity for the "worst case" scenario, where all the track switches would have to be changed. Therefore, adding a feedback capability giving the initial switch positions did not help in lowering the maximum power to be managed.

- With all the inputs from the sections of track showing occupancy, we were seriously concerned about running out of pins on the LabVIEW DAC board. Adding this feedback would have probably put us over the limit. We considered trying to multiplex the signals, but

felt that this would significantly increase the complexity of the testbed, and therefore its maintainability in the years ahead.

- By throwing varying number of track switches based on their initial configuration and the student solution, there could be significant variations in power requirements. We felt that this could actually make the electrical power management issue more complex rather than easier.

As part of our study of this issue, we realized that some simplification was possible. In Figure 1, there are several crossovers, involving four track switches plus an "X" section of track. We realized that all four of these switches should be in the same position, i.e. either all straight or all turned (straight running or crossover). This had the benefit of reducing the number of outputs required from the DAC board, but meant that all four switches had to be set as a group.

This led to the overall solution of initially setting all switches to "straight" and rippling the initialization to level power requirements. The students were also more comfortable with this approach since it provided a known initial condition.

There was also an issue of how the locomotive should traverse the testbed. In one approach, the locomotive would limit its travel in each direction using only half the testbed tracks, i.e. "keep to the right", and not allow the locomotive to cross over to the other half of the tracks. In this mode, the locomotive would cross from left to right on the bottom tracks, and right to left on the top tracks. This limited the number of solutions, and also had the advantage of requiring less equipment "up front". The alternative would be to allow the locomotive to travel any possible path using all the tracks, i.e., allow "reverse running" in railroad parlance. We felt it was prudent to "scale up" the project from its initial introduction, rather than accidentally make something that would be too difficult and discourage students from selecting this project in future terms, so we decided to use "keep to the right" rules for the initial introduction. The students gave us feedback that this did indeed make the problem too simple, and based on their additional recommendations we made "keep to the right" or "reverse running" an additional input that they would have to handle in finding a route.

Initial Reception

Both teams of students were extremely enthusiastic about this new project. At the start of the term, we informed them that they were an "alpha test" group, and that their feedback on the course materials we prepared and the schedule was actively solicited. We also told them there would probably be some "rough edges" since development of the testbed was still underway at the start of the year. This discussion actually increased their enthusiasm since they felt that they actually had a part in deciding how the project would run in future terms.

The students were generally satisfied with the written materials and descriptions that we supplied to them. In fact, the staff members were much more harsh critics than the students were. The students felt that they had a good idea of what needed to be done, and felt they were given the tools to solve the problem in a timely manner.

Allowing only "keep to the right" rules was a good idea. We got a better of idea of how the students would approach the problem, and gained insight on how to improve the testbed based on

their performance. The students enthusiastically endorsed the addition of a "reverse running" option for the project in the next term.

One idea we did not accept from the students was to start a locomotive from each end of the testbed and have them each find a path to the other end without colliding, essentially having the locomotives engage in a game of "chicken". Although this sounded like fun, we felt it would make the project too difficult for new college students, and also get away from the original mission of the project of having students become more familiar with digital logic principles, and that the students would start looking at more "ad hoc", less disciplined solutions to the problem.

Based on this success, we expanded to a "beta test" limited to several sections of the course. The students of opted for this project were also enthusiastic about it, and agreed with the assessment of the first group of students that adding the "reverse running" option added to the challenge of the project in a positive way. We also added an economic component to the project in terms of coming up with a cost per gate used, by type. This is the foundation for a design competition we plan to institute in the future.

Current Status

This is now a project available throughout the course, and a number of students have chosen to do it. Most of the students chose a partitioned solution, although no two teams partitioned the problem the same way. To our surprise, one team used a "brute force" approach, and took every permutation of inputs in one huge truth table. They then built a gigantic Karnaugh Map to come up with an optimal solution. Although this approach initially appeared to lack imagination, during their project progress presentation they explained that they had developed several software tools to help them in this effort, ultimately making their approach more sophisticated than the other teams. Having Freshmen developing the beginnings of CAD software was well beyond anything we expected.

We have somewhat become victims of our success. Use of the testbed has resulted in some problems with electrical connections. We are in the process of replacing breadboards with custom circuit cards and terminal strips in order to withstand the heavy use the testbed is receiving.

Remaining Tasks

The students liked the action provided by the switches flipping under the control of the VI they wrote, but felt that adding model train signal lights would add to the visual appeal of the testbed. Therefore, we plan to install miniature signal lights throughout the testbed, making it look like a real railroad. The plan is to install a signal light before each track switch, or group of track switches for the crossovers. If the locomotive were approaching a track switch where there is a choice, the signal will indicate, based on the setting of the track switch, whether the next section is occupied or not. If the locomotive were approaching a switch joining its section with another, the signal will indicate whether or not the switch is set such that the locomotive can pass through the switch.

When the testbed is first set up, we expect to see a mixture of red and green signals in no particular pattern based on the track switch settings and which sections of track are occupied.

When the student solution is fed into the testbed and the track switches set, there will be a set of green signals showing the path from one end of the testbed to the other. Seeing this path of green signals appear will provide additional visual feedback to the students, and just the sheer amount of color and lights should increase the excitement.

We also plan to modify the competition rules to have the cost of the gates factored into the team score from the beginning, rather than being a tie-breaker.

We also plan to have the students construct, as part of the project, a "track schematic", similar to what you would see at a railroad dispatcher's desk. The student will construct this out of foam board and Light Emitting Diodes, driven from LabVIEW. If there were a tie on "path cost" and "device cost", the quality of the track schematic would then be used to decide a winner.

Finally, if the project continues to grow in popularity, we will develop a second testbed based on our experiences with the first. This effort should go much faster than the first time around, and will include an emphasis on ruggedness from the beginning.

Summary

Overall, this project seems to be extremely popular with the students, and has achieved almost all the goals we set out for it. When the design competition is in place for this coming term, we will have achieved them all.

Our experience has been that it is not difficult to teach Freshmen the basic principles of logical design, sufficient for them to successfully complete the project.

The actual design of the testbed turned out to be more complex than we anticipated. We understood each component well, but the integration of them, especially digital logic controlling power electronics controlling model train equipment, was more difficult than we anticipated. Although we had consultants who helped us with each component, nobody seemed to have all the answers.

Costs to build the testbed can be a significant issue. The costs of the model train equipment can be significant, and the "cost density" of the testbed is high. In approximately eight feet by two feet of testbed, we have 20 track switches, four crossovers, 20 signals, a large assortment of model railroad "rolling stock" including a locomotive, plus assorted solenoids, wiring, electronics, etc. A typical model railroad has track switches relatively rarely – we have them every few inches. Also, crossovers are relatively rare, but with the testbed they are plentiful. Almost every component we used had high quantities associated with them, driving up the cost.

Also, with a model railroad, the hobbyist usually throws the track switches manually, and usually only one or two are changed at a time. Setting 20 track switches in rapid succession raised issues none of the hobbyists we used as consultants were able to able to answer. It was a learning experience for all of us.

Acknowledgements

Bibliography

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