

Model Railroading as an Active Learning Mechanism for Teaching Computer Science

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Abstract

Many computer science topics can benefit from active, hands-on learning techniques. This paper examines ways to use an HO scale model railroad to motivate students, provide active learning, promote hands-on experimentation, demonstrate abstract concepts with concrete examples, and generate a rich environment for student projects. The St. Thomas Academic Rail Road (S.T.A.R.R.) was designed and built with these goals in mind. It has been used by both the Computer Science department and the Manufacturing Engineering department to teach such varied topics as: sensors, digital electronics, microcomputer programming, microcomputer interfacing, robotics, and artificial intelligence. Future plans for the railroad include teaching vision, object-oriented programming, networking, web-based education, and real-time programming.

STARR uses the recently adopted international standard digital command and control (DCC) system to control multiple trains on the tracks. It uses the WinLOC software as well as handheld controllers connected to a local area network to issue commands to the trains. The layout is built using a flexible L-girder construction to allow maximum opportunities for student customization. National Model Railroad Association (NRMA) standards and recommended practices are followed to allow students to build to a known practicable specification with a reasonable assurance that their work will be compatible with the rest of the system. The layout is designed to provide a maximum of control opportunities and two allow at least two independent groups of students to work on separate projects without interference.

Some student projects explored in detail include a digitally controlled diesel horn miniaturized to fit inside the HO diesel shell, two different systems for detecting accurate gondola positioning (for automated loading), and a robotics system for loading/unloading a gondola.

Personal observations in using STARR as part of the course include increased enrollment, an increased enthusiasm for learning preparatory course material, an instant source of concrete examples when students are having difficulty grasping a concept, and an appreciation of the practical problems in implementing ideas in real physical systems.

1. The Genesis of STARR

The St. Thomas Academic RailRoad (STARR) was first conceived during the planning phase for a new science and engineering facility. Faculty were challenged to think of equipment needs in terms of what would best meet the needs of students. My primary responsibility was to design the computer science hardware lab in which we teach three courses: QMCS 340 - Digital Electronics and Microcomputer Interfacing; QMCS 380 - Artificial Intelligence and Robotics; and QMCS 270 - Laboratory Instrumentation in the Natural Sciences. My initial focus was on the Digital Electronics course. As part of this course, I always have students complete a semester project that involves constructing a digital

electronics interface to some real-world object and then placing that interface under microprocessor control. The greatest challenge for the student has always been project selection, followed by parts acquisition, followed by an exploration of the actual characteristics of the parts as compared to their stated characteristics. It occurred to me that a common source of projects from a rich enough problem domain would solve the first problem. A problem domain with readily available off-the-shelf inexpensive parts would solve the second. A problem domain with published, available, and certified standards (complete with tolerances) would help solve the third. After considerable reflection, I realized that my long-standing hobby of model railroading fit all of those criteria. This was not a totally new idea, as I was at that time aware of the efforts to use model railroading as a teaching tool at Carnegie-Mellon University and Eau Claire High School.

Thus began a two year long planning process prior to moving in to our new facilities in the O'Shaughnessy Science Hall within the Frey Science and Engineering Center. Goals and priorities for the railroad needed to be clearly stated so that a model railroad layout could be developed to meet those goals. Proposed layouts would dictate space requirements and room configuration. Finally, a clear plan of how this would fit into the curriculum, ideally in more than just one course, was needed to overcome the anticipated objection that I was merely finding a way to fund my hobby.

In the first stage of planning, I ordered a set of priorities as follows:

1. Safety
2. Learning
3. Functionality
4. Flexibility
5. Realism
6. Esthetics (like scenery)

This ordering of priorities dictated a rock-solid base for the layout. It dictated the design of a layout that was complex enough to present unlimited student challenges. It dictated a configuration that was functional in some minimal way without any student project needing to succeed. It dictated a construction technique that could be altered at any time to accommodate any proposed project.

As the planning for the layout and the building progressed, it became clear that the layout would also have to fit in the minimal amount of space, consistent with a student enrollment that would fill the lab. Since the lab was designed for 16 students, it was clear that the railroad would need to provide for work on at least two student group projects at a time. Thus evolved a layout with the following characteristics:

- Dogbone or C shape layout to minimize space, yet provide a large working perimeter
- Work areas at the top and bottom of the C shape (or ends of the dogbone), plus the ability to use the open part of the C (or middle of the dogbone) for a third work area
- Two independent main lines, with crossovers between them, to allow two independent projects or one large interdependent project for increased challenge
- Reversing loops for both main lines to add the complexity of reversing polarity when the train changed direction. This requirement and the previous one topologically implies an underpass/overpass
- Elevation steep enough to make throttle changes desirable, yet not so steep as to make them mandatory. From previous model railroading experience, that slope is about 3 ½ %
- Sidings on both main lines long enough to allow one train to pass another. This allows multiple trains to run in opposite directions on the same main line
- Electrical isolation of the two main lines in both rails to isolate project interference
- Multiple methods of train control - both analog and digital. This allows a traditional (analog) train to run in the event that the digital system hasn't yet been funded or isn't functional
- HO (1/87th) scale. This selection was made because HO scale is the most popular, parts are most available in HO scale, and HO parts are the cheapest.

The resulting track plan has 24 turnouts in only 135 feet of track (or just over 2 scale miles). This certainly put realism at the bottom of the priority list.

The layout did, however, present one very desirable feature. There were two rather large “work circles” near each end of the layout. They were pods ideally suited for the placement and use of the two Microbot robots used in the robotics course. The robots could be used to load and unload cargo from railway cars. This would provide a source of projects for the robotics students as well as the digital electronics students. The cars, of course, would need to be accurately positioned under the robot arm. This would be a sensor project that would need to be completed.

2. The Construction of STARR

Once moved into the new science facility, construction of STARR began with negotiations for a firm space commitment within the computer science hardware lab. Since I am not the only instructor using the room, I had to negotiate for as much space as possible. This started with an outline on the floor in masking tape of where the layout was to be placed. The masking tape was moved many times before the lumber to build the layout was ever hauled in. (It is a lot easier to move and re-size a masking tape outline than a model railroad table.)

A construction method called L-girder construction¹ was used for the benchwork. This allowed for a frame that was very light weight, very sturdy, very flexible, and yet relatively inexpensive. All the framework is made from readily available dimension lumber in only three sizes: 2x2, 1x2, and 1x3. The 2x2's are used only for legs. The 1x2's are used for cross-bracing, risers, and girder flanges. The 1x3's are used for girder webs and joists. Figure 1 shows the construction of the pairs of cross-braced legs with a built-in joist. Figure 2 shows the L-girders. Figure 3 shows the L-girders attached to the legs. Figure 4 shows the placement of the remaining joists just prior to installing the top. The structure is strong enough to hold several people on top of it, yet light enough to be lifted and moved. (Because of its physical size, it still requires four people to move it without risking damage to the layout, but it is a light load for each person.)



Figure 1



Figure 2



Figure 3



Figure 4

The top was constructed using the cookie-cutter technique in which a solid top is positioned, then sliced on both sides of all roadbed that needs to be elevated or depressed. The top consists of two layers:

the bottom layer is ½” plywood for strength, while the top layer is ½” homosote or sound board for sound deadening and ease of nail insertion. Figure 5 shows the top and side-skirts in place before the elevations are inserted. Figure 6 shows the process of slicing the top. Figure 7 shows the completed table, ready to track laying.



Figure 5



Figure 6

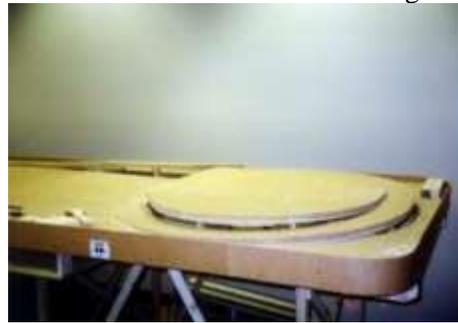


Figure 7

Trackwork was the next challenge. Fortunately, John Armstrong² provides excellent advice in that regard. He advocates the establishment and adherence to standards for the layout. This includes minimum overhead clearances, minimum clearances between straight sections of track, minimum clearances between curved track, minimum curve radii for different classes of service (mainline, yards, etc.), maximum grades, etc. Minimum standards for these dimensions are set by the National Model Railroad Association (NMRA).³ Because I deliberately wanted to restrict what equipment could be used in yards, I selected a minimum track radius of 18” for the yards. Because of space restrictions, I established a minimum track radius of 22” for the remainder of the layout. In line with the track radius minimums, I selected a number 4½ frog (Atlas #4 custom line) turnout to be the smallest turnout used. Already established was the 3½ % maximum grade to provide operating challenges without undue hardships. Easements were made into mainline curves, but superelevations were not. This allows for all equipment to run smoothly on the mainlines, and all but the large road diesel engines to operate in the yards. Construction practices generally followed the advice of Linn Westcott⁴. Figure 8 shows the completed trackwork.

3. Digital Command and Control

The way the computer controls the model railroad is perhaps the single largest design decision in the construction of an instructional system. One method was to do direct low-level control of all electronic functions using A-D and D-A converters, TTL-level logic I/O lines, relays, and sensors. Such was the approach taken by John McCormick^{5 6 7 8}. Another method was to use far less sophisticated control using digital PC-Lab I/O boards, as was done by Rodney Tosten⁹. A third method was to select one of the many competing off-the-shelf digital command and control (DCC) systems coming on the market. This would have been a difficult choice had not the NRMA recently established a standard for



Figure 8

DCC systems. The presence of a standard meant off-the-shelf interchangeable parts with known specifications in ready-to-run configuration.

The NMRA DCC standard uses the Lenz®/Digitrax® system to send command and control signals to the locomotives and other devices. This is a bipolar pulse width modulation technique sending packets of information onto the rails. Provision for a very long zero ending pulse provides for constant power to the rails to drive motors, lights, and analog locomotives. In effect, there is a LAN on the rails. For this reason, it is essential that nickel-silver rails be used and kept clean. In addition, the Digitrax® system uses a second LAN for connecting controllers¹⁰. This second LAN is run over 6-conductor cable using RJ-12 plugs and jacks. There is a PC interface cable available. DigiToys publishes a software package named WinLok that acts as a controller on a PC¹¹.

Having selected the Digitrax® system, the following equipment was purchased with departmental capital equipment funds:

- 1 - DHAT Athern wiring harness for inside an Athern locomotive
- 2 - DH120 2-function decoders for locomotives
- 1 - DH140 4-function decoder for locomotive
- 1 - DCS100 command station
- 2 - DT100 handheld throttle controllers
- 2 - UP3 universal panels for throttle attachment to controller LAN
- 1 - MS100 computer interface cable from controller LAN to PC
- 1 - PR1 computer driven programmer

I also constructed from scratch a power supply that would provide analog train control as well as power for the DCC system. This power supply contains analog momentum simulation for both start-up and braking, and provides pulsed DC at low voltages to keep the DC motors on the engines from stalling. This power supply was adapted from plans by Peter Thorne¹².

The layout was divided electrically into 20 blocks, isolated on both rails for maximum flexibility. Wiring to the rails was brought back to a terminal strip underneath the control panel. Figure 9 shows the power supply, DCC controller, and wiring.

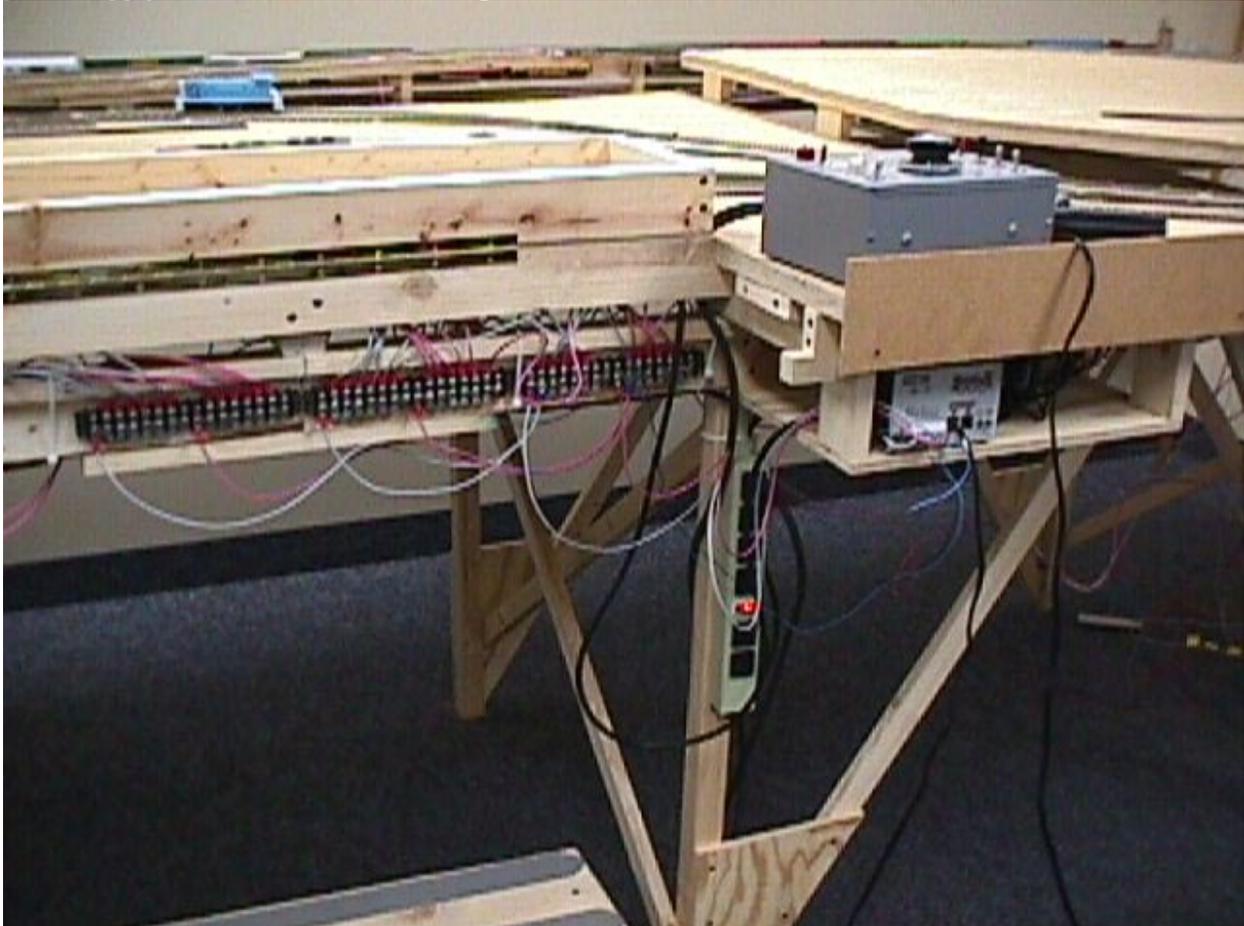


Figure 9

4. STARR Specifications and Statistics

The following table gives the critical specifications and important statistics of STARR, as currently constructed. There are no plans to alter these statistics, except for cost as more control features are added.

Minimum Curve Radius	18 Inches
Minimum Curve Radius - Main Line	22 Inches
Minimum Turnout	#4 ½ Frog
Minimum Turnout - Main Line	#6 Frog
Ruling Grade	2%
Maximum Grade	3 ½ %
Rail Material	Code 100, Nickel-Silver

Total Rail Length	125 Feet
Turnouts	24
DCC Controllers	3
Power Supplies	3
Tunnels	1
Bridges & Trestles	1
Electrical Blocks	20, Double Insulated
Dimensions	5' x 14'9"
Height	42 Inches
Cost	under \$2000
Reversing Loops	2

5. Digital Electronics and Microcomputer Interfacing on STARR

The bulk of the construction took place during January, 1998, in preparation for my QMCS 340 - Digital Electronics and Microcomputer Interfacing course starting in February. Word got out to the students as to what was going on in the Computer Science Hardware Lab. Before I knew it, the course had a record enrollment. 16 excited students greeted me on the first day of class wondering when they could start work on the railroad. Students I had never seen before appeared in the lab to work on the railroad and student projects throughout the semester.

The railroad proved to be a constant motivator throughout the course. I could constantly relate course material to physical equipment and electrical properties of the railroad. When it came time to select projects, there was no shortage of ideas, all related to the railroad. However, translating ideas into circuits and software can be a formidable task. Fortunately, Rutger Friberg has written an excellent series of books on model railroad electronics and hardware/software interfacing with railroads¹³. These books were in constant use as students adapted his designs and ideas to the railroad. Here is a brief description of the student projects, and their results:

One project was a railway crossing flashing signal and blocking gate. While this may seem a "simple" project in an analog world, the problem has some interesting learning challenges in the digital domain. The motor used for the blocking gate was a stepper motor. It had to lower slower than it raised, and had to account for obstacles that might cause it to "slip" on the way down. This project had a successful prototype on the breadboard.

Another project was an automobile lift bridge over the tracks. The logic, sensing, and safeties for this project were daunting. You could not lift a bridge when a car was on it, nor lower a bridge on a train, nor power a train through the track when the bridge was down. The train had priority over the cars, but that was obviously not absolute. This project failed in prototype due to erratic sensor behavior. I believe now that the failure was due to dirty track. But in retrospect the project was too difficult. They had the same stepper motor problems to contend with as the blocking gate project, but far more sensing and logic.

A third project was the sensing of car position on the track in anticipation of the robotics course to be offered the following fall. The goal was to devise a system to accurately detect if a scale 50' gondola car was correctly positioned on a siding to be loaded by a robot. The students elected to work with photocells nestled between the rail ties, and activated by ambient light. They had to process fuzzy signals from imprecise sensors in real-time as the train was moving. Although the final project required far too much hardware to be practical for permanent installation (three breadboard, a digital trainer, and a microprocessor trainer), the project was a success.

The fourth project was a diesel horn activated by an auxiliary control line from the DH-140 decoder located in a diesel. At first, I considered the project too trivial for a course project. However, the students started work on it at the beginning of the semester and I told them that once they got it working we could find some way to extend the project. Getting the circuit to work on the breadboard was

indeed somewhat trivial. Miniaturizing the circuit to fit inside of an HO diesel locomotive was a much greater challenge. Fitting a speaker and a capacitor large enough to resonate at AF were only the most obvious challenges. Once the circuit was re-designed for miniaturization (lower operating voltage to reduce capacitor size, use two smaller capacitors to make package flatter, etc.), the circuit was placed in the locomotive. A circuit that worked fine on the breadboard worked very badly in the locomotive. The culprit was electrical interference from two sources: the arcing brushes on the DC motor and the square waves for the DCC signals on the rails. The project suddenly took on new engineering dimensions that led them into some interesting research and creative solutions. They presented a paper on their efforts to the St. Paul Radio Club. Figure 10 shows the completed project from the outside and figure 11 shows it from the inside.



Figure 10

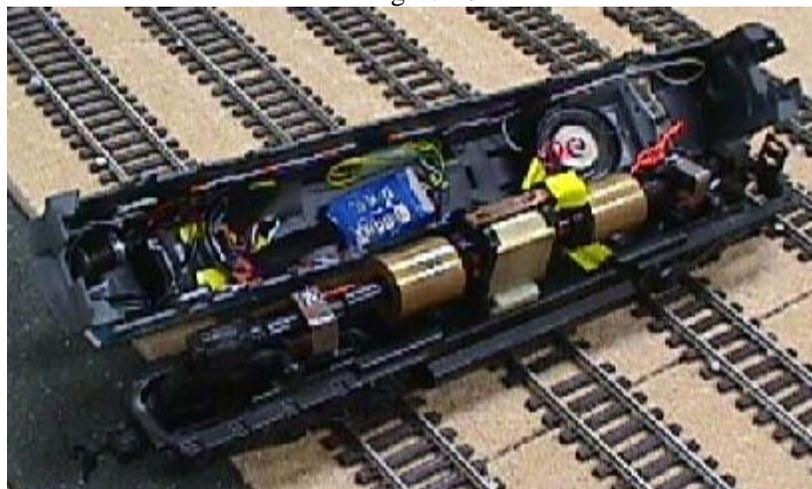


Figure 11

6. The Graduate Programs in Manufacturing Engineering Sensors Course

Word about the model railroad in our lab spread to various areas of the campus. When I explained some of the challenges presented by the railroad, Dr. Jeff Jalkio in our Engineering department became quite interested. He had been looking for sensor projects for his graduate students, and STARR met all of the requirements. We outlined three projects, to take place during the same semester as the Digital Electronics and Microcomputer Interfacing course. The first was a car position sensing system, since I did not know for sure that my Digital Electronics students would come up with a workable solution for my robotics students to use the following fall. The second was block detection for all the blocks so that students could use the information for train control, route control, collision avoidance, crossing gates, drawbridges, etc. The third was a car locator system so that the robotics students could load the correct car with the correct load. The purpose of the sensors course is quite different than any computer science

course. Since this is an engineering course, they need to consider cost/benefit, make vs. buy, system complexity, and satisfaction of customer requirements.

For the car position sensing problem, they came up with four pair of infrared emitters and detectors placed on either side of the roadbed, 50 scale feet apart. The value of standards really proved its worth in this project. The students accessed the NMRA web site to obtain detailed specifications for recommended standards and practices. The graduate students were able to use these standards to build a precision location device for 50' gondola cars. The standards specified how much clearance they needed to allow near tracks, how high the car might be above the rails, how much variation there might be in the distance between cars, etc. This allowed them to build their sensing system in their own lab while the remainder of the railroad was being used to teach Digital Electronics in the computer science hardware lab. This successful project is capable of positioning a car within one scale foot ($1/87^{\text{th}}$ of an inch). Figure 12 shows the completed project in its unwired state.



Figure 12

For the block detection problem they performed a classic buy vs. build analysis. Since Digitrax® makes a block detection system for DCC railroads, the students determined it was most cost effective to purchase the following additional equipment for our laboratory:

- 20 - BD-1 block occupancy detectors

- 3 - DS54 quad stationary decoders for use with the above block occupancy detectors

Unfortunately, wiring these up to the railroad near the end of the semester when the Digital Electronics students were trying to work on their projects proved quite disruptive. The railroad was never planned for two different courses working on different styles of projects at the same time.

For the car locator system, a bar coding system was planned. Each car would be bar coded and a bar code reader would be installed in the yard. Unfortunately, the price of the equipment was beyond the scope of the Engineering Department's budget, so that project was scrapped. It has been left as an area for further research.

7. Artificial Intelligence and Robotics on STARR

In the fall of 1998, I taught QMCS 380 - Artificial Intelligence and Robotics, again using the railroad as a source of examples and project ideas. This course, too, attracted a full section of 16 students with a number of students on a waiting list. The obvious course project is to load railway cars with the robot. The best project for the course loaded moving cars from an automated feeder. It used the sensor system developed by the digital electronics students, and was able to use the output from their system as direct input into the robotic controller opto-isolators. Figure 13 shows the working project.

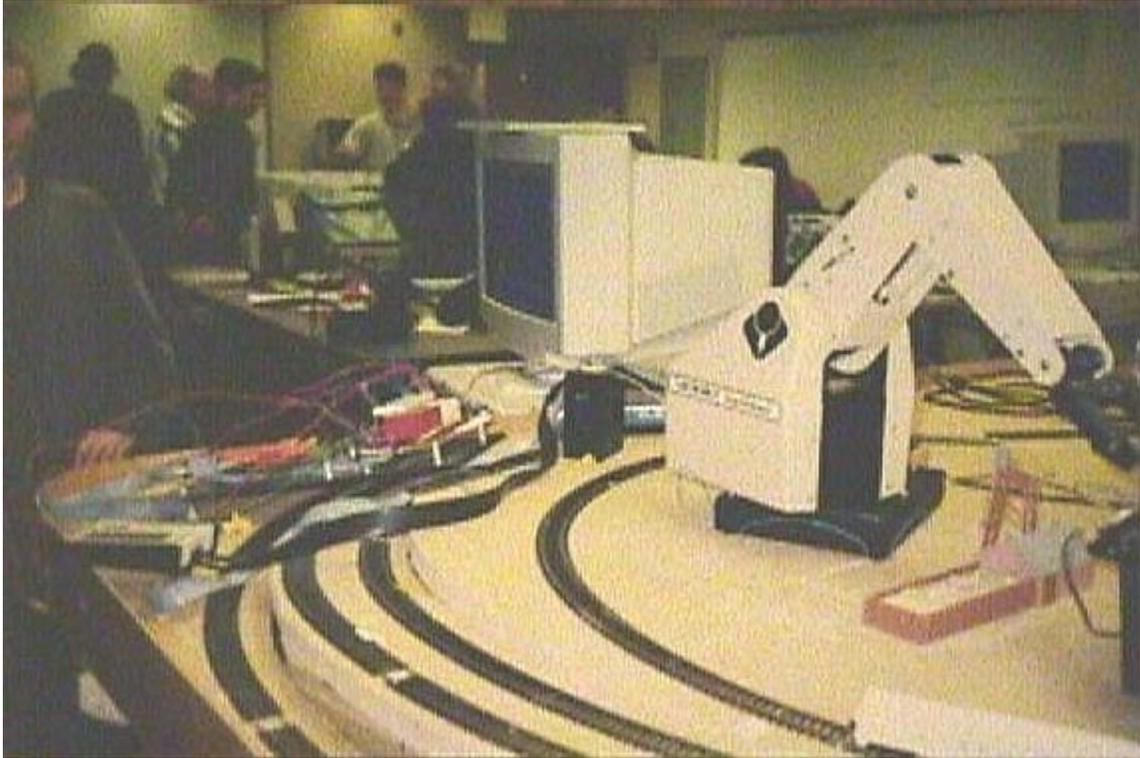


Figure 13

8. What Can Be Taught with a System Like STARR

Based on what students have demonstrated they have been able to do using STARR, it has shown that it can support the teaching of the following topics:

- Digital Electronics
- Microcomputer Programming
- Microcomputer Interfacing
- Sensors
- Robotics
- Electronics

Based on efforts by Dr. McCormick, it has been shown that a model railroad can support the teaching of:

- Digital Process Control
- Ada Programming
- Real-Time Software
- Software Engineering

Based on efforts by Rodney Tosten, it has been shown that a model railroad can support the teaching of:

- Artificial Intelligence
- Operating Systems

Dr. McCormick has plans to build a reproducible system for use in the 500 schools that have already expressed an interest in establishing model railroads for computer science instruction. Schools in Madrid, Spain and Rio de Janeiro, Brazil have already duplicated his railroad, demonstrating the feasibility of duplication. He envisions that such a system could be used to teach:

- Artificial Intelligence
- Graphics
- Networks
- Operating Systems
- Programming Languages
- Compiler Construction
- Software Engineering
- Introductory Computer Courses

I envision that a DCC system similar to STARR could easily be used to teach the following additional topics:

- Networking
- Web Interfacing
- Vision

The reason networking would be a logical choice is because of the presence of two local area networks already running on the system. The LAN on the rails is well documented, and inexpensive hardware exists for decoding the signals. The data rate is slow enough the students can “see” the signals with a good oscilloscope. The LAN between the controllers is proprietary, but the people at Digitrax have expressed an interest in working with experimenters.

There have already been demonstrated efforts to interface a DCC model railroad with the web. The University of Ulm in Germany has a simple railroad, similar in layout to that of Rodney Tosten, controllable from the web¹⁴. Since there is already an off-the-shelf interface to the PC, extending that interface to the Web should be an interesting research project for a motivated student.

Computer vision is a very promising application of the model railroad, primarily because of the existence of TrainCAM. TrainCAM, shown in figure 14, is an off-the-shelf product manufactured by Video Research¹⁵



Figure 14

TrainCAM is a digital camera and transmitter mounted inside a dummy locomotive. When pushed ahead of a real locomotive, the user can receive on a television monitor or a video capture board (such as a Stinger Pro¹⁶). This provides a digitized image inside the computer ready for processing. Because the train is on a fixed track, images will “almost” repeat themselves once per rotation around the layout. This allows for experiments in pattern recognition and neural network training for vision.

9. Conclusions and Areas for Further Research

Model railroads have been shown to provide a rich environment for active student learning. They allow students to deal with real problems in a concrete physical environment. They can be used to teach a wide spectrum of the topics typically covered in a computer science curriculum. They are no more expensive to build than the cost of a personal computer. Future research includes demonstrating the feasibility of teaching courses in all of the topics mentioned in section 8.

¹ Westcott, Linn H. *How to Build Model Railroad Benchwork*. 4th Printing. Milwaukee: Kalmbach Books. 1987.

² Armstrong, John. *Track Planning for Realistic Operation*. 2nd Edition, 4th Printing. Milwaukee: Kalmbach Books. 1986.

³ National Model Railroad Association. *NMRA Standards and Recommended Practices*.
http://users.vnet.net/paulrver/st_welco.html

⁴ Westcott, Linn H. *HO Primer: Model Railroading For All*. Milwaukee: Kalmbach Books. 1978.

⁵ McCormick, John W. "Using a Model Railroad to Teach Digital Process Control." *SIGCSE Bulletin*, Vol 20, pp 304-308. 1988.

⁶ McCormick, John W. "A Laboratory for Teaching the Development of Real-Time Software Systems." *SIGCSE Bulletin*, Vol 23, pp 260-264. 1991.

⁷ McCormick, John W. "Using a Model Railroad to Teach Ada and Software Engineering." *ACM Proceedings of the Conference on Ada*, pp 511-514. 1991.

⁸ McCormick, John W. "A Model Railroad for Ada and Software Engineering." *Communications of the ACM*, Vol 35, pp 68-70. 1992.

⁹ Tosten, Rodney S. "Using a Model Railroad System in an Artificial Intelligence and Operating Systems Course." *SIGSCE Bulletin*, Vol 25, pp 30-32. 1993.

¹⁰ Digitrax. 450 Cemetery St. #206. Norcross, GA. www.digitrax.com

¹¹ WinLok 2.1: Digital Model Railroad Command Control Software for Windows. Lawrenceville, GA: DigiToys. 1998.

¹² Thorne, Peter J. *Practical Electronic Projects for Model Railroaders*. 2nd Printing. Milwaukee: Kalmbach Books. 1975.

¹³ Friberg, Rutger. *Model Railroad Electronics 1, 2, 3, 4, and 5*. Stockholm: Allt om Hobby Publishing Company. 1997.

¹⁴ Interactive Model Railroad - University of Ulm, Germany. [Http://rr-vs.informatik.uni-ulm.de/rr/](http://rr-vs.informatik.uni-ulm.de/rr/)

¹⁵ TrainCam. Video Research, 2010 E. Hennepin Ave., Minneapolis, MN.

¹⁶ Stinger Pro Capture Card. Video Labs, 5960 Golden Valley Hills Drive, Golden Valley, MN.