# Racing to Understanding:
# Instrumentation Lab with Radio-Controlled Cars

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## Abstract

Freshmen engineering students are being introduced to electronic measurement and instrument control using radio-controlled cars in a new Introduction to Engineering module.  The seven-week module is conducted as a hands-on laboratory experience using HP VEE, a commercial software package for instrument control and graphical programming.  Engineering content includes basic descriptions of signals, simple electronics, use of oscilloscopes, function generators, multimeters, and power supplies, open-loop control, user interface design, and the details of HP VEE and GPIB.

The Radio Shack Black Wolf II cars used have proportional controllers with joysticks for steering and velocity, and use pulse position modulation on a 27 MHz carrier.  Cars with four bands are available allowing students to run several cars simultaneously.  The controllers were modified to allow students to examine control signals and the carrier.  They measure pulse characteristics and deduce the control scheme.   Next students create their own control signals with HP VEE and download them to a function generator that bursts them to the transmitter. The HP VEE panel must be designed with an intuitive user interface.   Finally students must devise a control plan to navigate a rally course in the lobby of the engineering building.  The "final exam" is their rally performance.

## Introduction

Helping freshman engineering students become familiar with the "real world" practice of engineering while meeting heavy first-year curriculum requirements has been a continuing challenge[1,2].  At Boston University this problem is addressed with a required 4 credit course, "Introduction to Engineering", organized as two half-semester modules.  The course is offered each semester to half of the freshmen class.  The other half takes a required course on engineering computation.  Typically 8-12 faculty from the College's four departments offer modules. Other recent modules have included CAD, machine design, electronic music, image processing, the human genome, and fiber optics.

Each module is intended to be a stimulating and confidence-building experience.  Students are encouraged to explore their engineering interests and "tinker" with different majors as much as possible.  The goal is not to create an early cognitive lesson as much as to demonstrate that engineering can be relevant, interesting and even fun! Modules usually introduce aspects of a particular engineering discipline, cover some basic engineering problem-solving skills, cultivate professional and independent learner attitudes, and bring first-year students in contact with engineering faculty[3].  Modules operate independently, but a course coordinator administers

registrations and assigns a course grade based on the two module grades. Students are given short descriptions and identify several preferred modules during preregistration. They are assigned to their two modules according to preferences, schedules, and available class openings.

Freshman modules focus attention on the early experiences of engineering students, as encouraged by ABET EC2000[4]. The module described in this paper is "Computer-Controlled Instrumentation and HP VEE". It is laboratory-based and uses a personal computer to collect and generate signals to operate a radio-controlled car. This application has generated curiosity in many students and attracted several former radio-controlled car owners. The module was fully enrolled at 28 students each offering.

Laboratory Resources

This module was conducted in an existing undergraduate electronics laboratory having 30 stations configured for sophomore and junior circuits, electronics, and communications courses. Each has a PC-compatible computer with a 100 MHz processor, 16 MB of RAM, a 1.0 GB hard drive, and an IEEE-488 General Purpose Interface Bus (GPIB) interface card. The GPIB bus connects an HP33120A 15 MHz function generator, an HP54600B 100 MHz digital scope, a HP E3631A triple DC power supply, and an HP34401A multimeter. The stations are not networked, but a printer station is available for 'sneaker net' printing. Costs per station, including the PC, are under $5000. HP VEE 4.0 was used under Windows 95. License packs are less than $20/station and free evaluation and run-only versions are available on the Internet.



Figure 1. BlackWolf II radio-controlled car and controller

Six Radio Shack BlackWolf II radio-controlled cars, controllers, battery packs, and chargers were purchased. The cost per car was less than $70. The controllers have steering and velocity joysticks and each car has a two-speed motor. Their outdoor control range is 50m; indoor range depended on the building construction. Large lobby areas worked best and generated a lot of public attention. Since the cars are sold with only four distinct frequency bands, two cars were used as spares during the final rally competition.

The controllers were modified with 9-pin DIN connectors to supply power, measure controller signals, and insert student-generated controls from the benchtop. These additional parts were less than $5/controller and greatly improved student facility with the controllers. Rather than

trying to connect to pins or traces in the controller, important signals were available outside on simple test clips.

Control Operation

Steering and velocity control uses a form of pulse-position modulation. The controller first generates a local squarewave at 68 Hz. The joystick potentiometers modify this squarewave to set the cutoff levels of two amplifier stages whose outputs are inverted and added back to the original squarewave. This creates three 0.2 ms pulses separated by time delays that are dependent on the joysticks' deflections. This pulse group drives the bias point of the transmitter output amplifier to turn off the carrier during the pulses' on periods. The carrier operates between 28.1 MHz and 28.5 MHz, depending on a car's band.

The receiver detects the time delays between the blanking, and generates the appropriate controls to the motor and steering mechanisms. Figure 2 shows a typical control signal from the joystick stage.
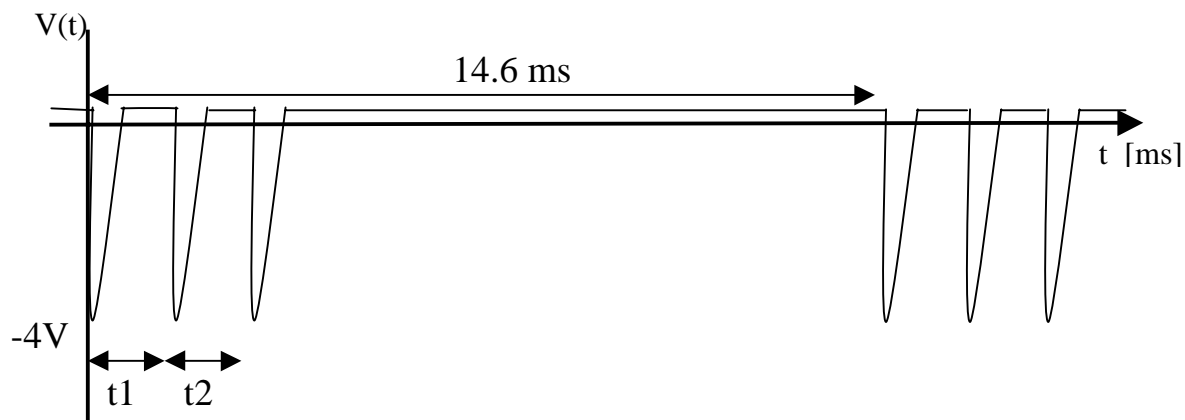


Figure 2. Schematic of controller blanking signal generated from joystick inputs. Each pulse blanks the 28 MHz transmitter carrier. Joysticks vary t1 and t2.

Each joystick can move over a range of ±20°. The steering joystick changes duration t1 between the first and second pulses while the velocity joystick changes t2 between the second and third pulses. Figure 2 shows an idealized control action plot, in terms of t1 and t2. Note that at t1 = t2 =1.5 ms puts the car at rest, steering straight ahead. Ultimately, the joystick control is nonlinear. The degree of steering and velocity control at the car is nearly 100% after only 5 degrees of movement of the joystick.

Control action is also affected by the mechanical suspension of the car. The plastic parts are rugged, but loosely fitted. Under human control, with visual feedback, this is not important. But with open-loop computer control, the biases are critical. The steering bias of the suspension tends to vary, especially if the car strikes an obstacle. Similarly, the velocity deadzone varies with the gearing backlash. These make fine steering and slow velocity control difficult.

t2 (velocity)

2 ms — Forward

Velocity = 100%, forward
Steering 100% Right
(2 ms, 2 ms

1 ms — Backward

Velocity = 0
Steering straight
(1.5 ms, 1.5 ms )

Left      Right
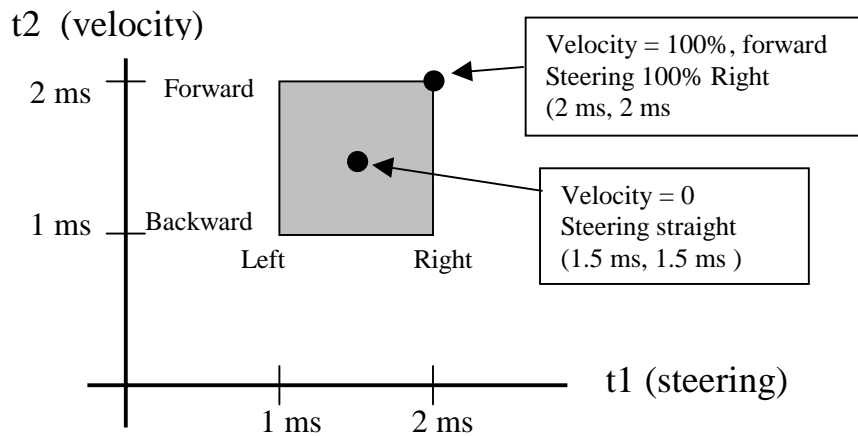
t1 (steering)

1 ms   2 ms

Figure 3. Control region in t1-t2 space. The steering joystick sets delay t1; t2 is set by the velocity joystick.

Knowledge Outcomes: By the end of this module, students should know:

1. How to specify signals in magnitude, time and frequency
2. The physics and engineering of a simple communication link;
3. Common circuit elements and their schematic symbols;
4. Electronics laboratory safety and measurement procedures;
5. Fundamental HP VEE graphical programming elements.

Skill Outcomes: By the end of this module, students should be able to:

1. Use a clear, organized solution procedure for analytical problems;
2. Read and make an accurate schematic of simple electronic circuits;
3. Program in HP VEE for signal design and instrument operation;
4. Recognize simple electronic circuit board components and traces.
5. Operate the oscilloscope, power supply and function generator.

Attitude Outcomes: This module fosters the following attitudes:

1. A positive feeling towards the electronics instrumentation area and its challenges;
2. An increased appreciation for the way a practicing engineer approaches open-ended problems;
3. An appreciation for the importance of clarity, organization, accuracy, and neatness in engineering calculations;
4. A more mature attitude toward the teacher-student relationship in a learning environment;
5. An increased sense of responsibility for one's own education and learning.

**Table 1. Intended course outcomes**

The module meets twice a week in the electronics laboratory for 1h 40 m, for a total of 13 sessions (one-half semester). The detailed schedule is shown in Table 2 below. Each class is motivated by an engineering task, e.g. "determine the controller signals associated with joystick actions" or "test the car response to your simulated signals." These tasks lead to discussions and identification of needed information or skills. New conceptual material is discussed first, e.g. reading a schematic. The second part of each class is always hands-on, concentrating on the use of the instruments, measurement of the controller signals, or HP VEE programming to develop control signals. Towards the end of the module, the entire period is dedicated to HP VEE and instrument activities. This structure attempts to demystify engineering and the controller technology, recognizing that freshmen arrive with a wide range of skills and confidence[5].

HP VEE is a graphical programming language[6]. Its programs are implemented by choosing iconic elements (data inputs, functions, logical operators, instrument panels, displays, etc.) and interconnecting them with "wires" that carry data objects and control signals. Virtual sources and displays can coexist with real interfaces with the benchtop instruments. The GPIB communication and control details are often hidden behind intuitive panel drivers. Integration of Windows 95 tools makes the environment user-friendly and development of working programs is rapid compared to approaches using text-based languages.

Grading of the module is based on quizzes, homework, and performance of the student controller at an end-of-module rally. Each week includes a 10-minute quiz to reinforce a related skill like specifying a signal or predicting the operation of a HP VEE program. Weekly homework is assigned and graded. Homework is used to consolidate skills or to develop strategy for upcoming lab work. As this is an introductory course, students are given ample opportunities to earn a good grade. They are encouraged to restudy the material and take a makeup quiz to show mastery if their weekly quiz goes poorly. Students may also submit homework "rebids" to recoup lost homework marks. Unlike the homework, which is problem-based, the rebids involve more writing. Rebids are formulated as memos from an engineering manager to the student, asking for an analysis, design, or presentation materials related to an earlier homework. Students must submit their rebids as memos to their manager, supported by their analysis or design work. The rally, held on the last day of the module in a lobby area of the engineering building, is the final grading component. Four benchtop setups are placed on carts and moved to the lobby, allowing simultaneous runs of a car from each band. The rally course consists of driving 5 m forward, through a defined 'gate', and returning to the starting line. Students are timed and their score is based on their best run-time in the 25-minute window they have for setup and driving. The performance time constraint favors students who have invested in an effective user's interface, or pursued more advanced equipment options like storing waveforms instead of generating them on the fly.

| Class | Design | HP VEE | Task |
|:---:|:---:|:---:|:---|
| 1,2 | Intro | Fundamentals Signals | Develop system view of BlackWolf car; Create an HP-VEE pulse generator |
| 3,4 | Specs | Scopes; Function Generators | Spec and create AM signal in PC; Use oscilloscope to measure function generator |
| 5,6 | Schematic | Signals; Carriers | Read controller schematics and identify signals; Observe control circuit and its signals |
| 7,8 | Simulation | Generate Waveforms | Create signals to accomplish driving functions; Spec and create simulated signals on bench |
| 9,10 | Integration | Communications, Control | Describe communications channel; Control vehicle on benchtop with HP-VEE |
| 11,12 | Testing | Choreography; Debugging | Create final signal plan for competition Test driving signals with working cars. |
| 13 | Delivery | Competition | Compete on the course |

Table 2. Schedule of module activities and classes

HP VEE Controller Development

Student control of the cars is achieved by simulating a control signal in HP VEE and injecting the signal into the transmitter amplifier to create appropriate carrier blanking intervals. Students initially discover the controller's 68 Hz blanking pulses while learning to use the scopes. They then pick a time step for simulating the pulses with adequate resolution. Initially the students specify the locations of pulses in terms of actual time increments, using built-in iteration, if-then-else, and waveform display blocks in HP VEE to create and display an array of -1s and 0s. This is later refined to include an intuitive interface in terms of desired control actions (e.g. right-left, 0-100%; forward-backward, 0-100%). HP VEE knobs and sliders can be used to make a convenient virtual controller interface on the screen.

After creating an appropriate control action data array, the data are sent over the GPIB to the function generator, where they are stored as one of four possible user-generated arbitrary waveforms. The HP VEE function generator panel driver, which appears on screen with intuitive controls, is used to set frequency and amplitude and activate the arbitrary waveform. The function generator output is inserted at the transmitter input signal point and the appropriate blanked carrier is broadcast, making the car move.

Students quickly recognize that they need to include command duration in their control strategy, as well as commands for steering and velocity. They next modify their HP VEE program to input the time in seconds of command duration. This is converted to signal periods and the function generator is used in burst mode to output a precise number of control signals, giving the car a fixed time of operation. A sample of a final student HP VEE program is given in Figure 3.
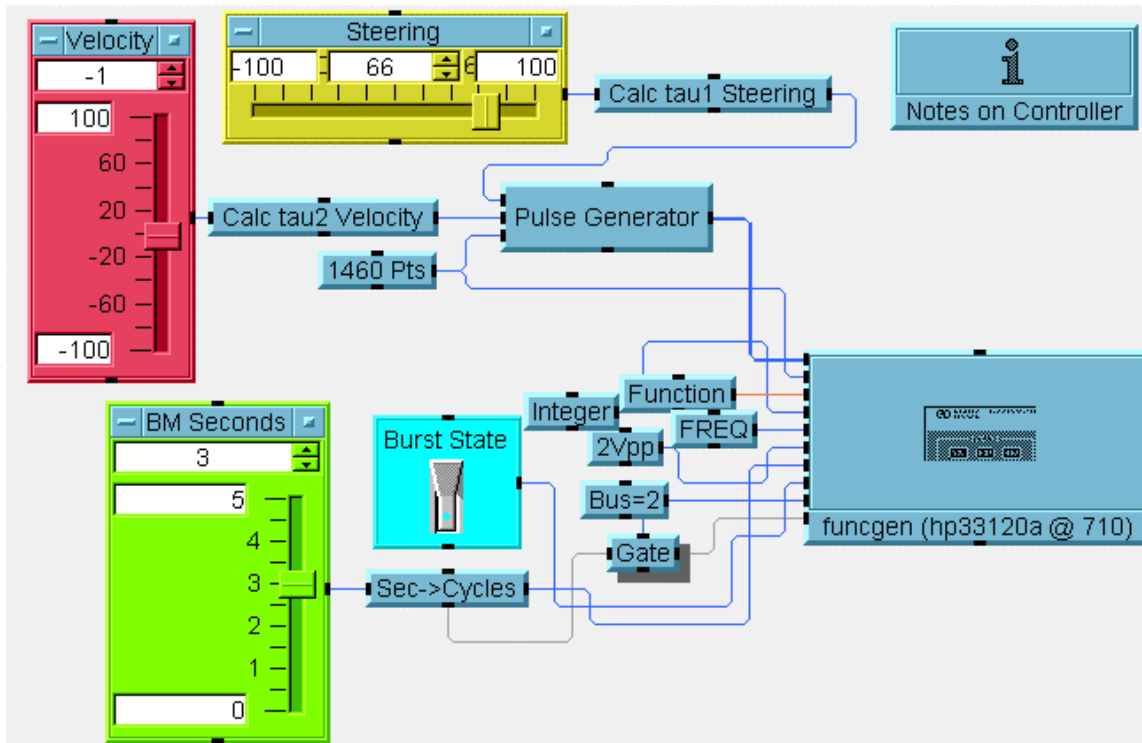
Figure 3. Iconized final controller program to simulate joystick and time control of the BlackWolf II car. 'Burst State' switch allows continuous control signals for testing.

Three complications made computer control more erratic than hand driving with joysticks. First, all control was open loop. With hand controls, visual feedback allows rapid correction of errors. With HP VEE and the BlackWolf II cars, no feedback link was available. Second, HP VEE and GPIB can have substantial time delays when considering driving time scales. Time delays arise while calculating the control array, moving it over the bus to the function generator, and while setting up and initiating burst mode operation. The time delays are strongly dependent on array sizes and hence, on the signal resolution when using a fixed time step. Time delays of several seconds were common, making it impossible to execute dynamic changes while driving. The cars had to be commanded to drive in a certain steering/velocity configuration for a set time, after which a new signal would have to be reloaded. Finally, most control actions would be followed by a period of uncontrolled coasting, during which steering was unpredictable.

Evaluation

Informal student feedback was elicited after each class with an anonymous "minute paper," asking two questions: "What was the most important idea in today's class?" And "What issue is still unclear after today's class?" Minute papers helped ensure that common questions were addressed and that ineffective exercises could be deleted or modified in the next offering. Students reacted most positively to the hands-on aspects of the module.

The module was formally evaluated at the last meeting with a standard student questionnaire that sought feedback about the instructor and the course. Generally student response was positive towards the applied problem of controlling the cars, and towards the strongly hands-on

experimental nature of the course. Students liked being in the electronics lab as freshmen and learning to use equipment that will later be part of their curriculum.

Frustration was high among some students, especially those who felt their computer control of the cars was unsuccessful. Some attributed this to the course design, saying that it was an ambitious module that tried to cover too many aspects of measurement and HP VEE. Others complained that the cars were inadequate because of their loose suspension and coasting behavior. Finally some complained that the course was not well organized, citing the need to go back and redesign components several times to account for non-linearity, car dynamics and GPIB data delays.

Offering this module at another college would require adequate instrumentation, computers, and software support. Any standard electronics hardware compatible with GPIB (or RS232) control could be used, as long it supports signal storage and burst mode operation. LabVIEW could be used to develop the instrument control system and simulated controller signals. Many radio-controlled car models are available, and most from Radio Shack use a similar controller. Course materials can be found at http://people.bu.edu/mfr/EK130 .

Conclusions

A seven-week module using computer-based instrumentation to study and ultimately control a small radio-controlled car has been described. The module provides an appealing and rich context for freshmen to explore basic electrical and computer engineering concepts. Students leave the module with an introductory proficiency in electronics instrumentation, familiarity with schematics, and experience in graphical programming in HP VEE. Student reaction to the module has been positive.

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Biography

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