Using LEGO® Bricks to Conduct Engineering Experiments

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Abstract
When developing a new laboratory experience for undergraduates, the primary logistical requirements tend to be low cost and high availability. One popular method of meeting these somewhat conflicting requirements is to create on-line laboratory experiments. This paper explores another method that utilizes the LEGO® programmable brick (RCX) as a portable data acquisition system. Students both design and conduct the experiments at home. Students also have the ability to conduct personal engineering experiments to investigate phenomena of personal interest.

In this paper, we describe several experiments that we have conducted with the LEGO® programmable brick and Robolab (LabVIEW) that give students first hand experience with "typical" engineering concepts that would normally be covered in sophomore or junior-level laboratory courses. Examples on data acquisition, numerical methods, dynamics, statics, motor performance, fluid dynamics, feedback control, and strength of materials are presented.

1. Introduction

Whether it be a desire to incorporate laboratory experiences in traditional lecture courses so that the experiments are conducted at the same time the content is presented or simply the desire to revise an existing laboratory course, many universities are attempting to modernize undergraduate laboratory experiences. Coupled with diminishing budgets and increased accountability for expenditures, many universities are turning to on-line, virtual laboratories. Virtual laboratories are often cited as being cost effective and having high availability to the students. This method does not give students the hands-on experience, however. Our solution to address the issue of modernization bounded by economics is through using LEGO® bricks. We present several examples in this paper of how the LEGO® RCX programmable brick can be used to teach traditional engineering laboratory experiments.

These popular interlocking bricks are not new to the college campus. A cursory literature search of the ASEE and IEEE proceedings revealed over 200 papers concerned with the use of LEGO® bricks in some form or another. While many of the papers dealt with their use in a research environment, e.g. the humanoid robot that displays emotional expressions in response to direct physical contact [1], over half of the papers concentrated on the use of LEGO® bricks as an educational tool.

Within the realm of educational studies, LEGO® bricks have been used at all ages. The literature describes many uses for K-12 enrichment programs which are not within the scope of this paper (e.g., [2-5]). Restricting the literature review to tertiary education reveals that both programmable and non-programmable bricks have been used to teach engineering principles (e.g., [6, 7]). Further focusing on studies dealing the use of the RCX programmable brick reveals many papers describing a wide variety of projects and courses ranging from robot competitions (e.g., [8, 9]) to computer programming (e.g., [10]) to project based learning (e.g., [11-17]).

What is obvious from the literature is that the RCX can be used in a variety of ways to increase student learning and excitement. In this paper we describe how the RCX can be used to supplement or even replace traditional engineering laboratory experiences. The examples include many of our own devising, plus a review of the few found in the literature [18-23]. Our goal with this paper is to show some of the different ways LEGO® bricks can be used to teach engineering principles. It is not meant to be an in-depth review for changing a specific class but rather a set of ideas for people to use to make a number of classes more compelling for the students. We have found the LEGO® sets bring with them student enthusiasm and excitement and think it is a great way to show students why they have to learn the math and physics to become good engineers.

2. Hardware and Software

The Mindstorms product line is named after the book **Mindstorms** by Dr. Seymour Papert at the Massachusetts Institute of Technology's Media Lab [24]. Somewhat confusing, there are actually two different Mindstorms product lines: retail "Mindstorms" and "Mindstorms for Schools," with the later being the product line aimed specifically at the educational market.

Figure 1. The Mindstorms for Schools (left) and retail Mindstorms (right) versions of the RCX.

The Robotic Command eXplorer (RCX) programmable brick is the main Mindstorms component. The primary difference between the "retail" and "Mindstorms for Schools" versions is the absence of the external 9V DC adapter port on the retail version (Figure 1). This port is very useful for long data samples (e.g. temperature overnight). As shown in Figure 2, both versions have six ports: three input ports (1, 2, and 3) and three output ports (A, B, and C). The RCX also comes equipped with a LCD screen for displaying useful information, four buttons for activating the RCX, an internal speaker for playing sounds, and an infrared (IR) communications port.

Some of the available input and output devices for the RCX are shown in Table 1. Not shown are the capacitor and solar panel since they are neither input nor output devices for the RCX. If the standard sensors or motors aren't enough, there are dozens of input and output devices that can be purchased from third party vendors or can be made by students. These are beyond the scope of this paper, but there are several good books and websites (e.g. [25-29]).

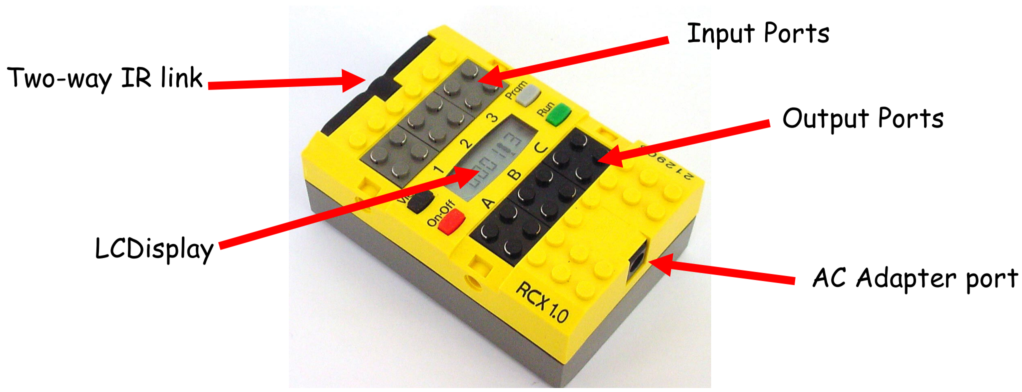
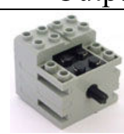
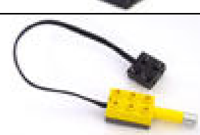


Figure 2. The RCX programmable brick.

Table 1. LEGO® input and output devices

Output Devices		Input Devices	
	Motor (internally geared)		Touch Sensor
	Micromotor		Light Sensor
	9V Motor		Rotation Sensor
	Sound Element		Temperature Sensor
	Lamp Element		Camera

While there are many programming environments for the RCX (e.g. mindscript, NQC, pbForth, legOS, and LeJos), this paper focuses on the use of Robolab. Robolab was jointly developed by National Instruments (Austin, TX), Tufts University, and LEGO® Educational (Enfield, CT). The primary reason for concentrating on Robolab is that students can learn to program the RCX quickly with very little instruction and with no previous programming experience. The added benefit is that they are introduced to LabVIEW, which is the most common data acquisition package currently on the market and is used in most industry and government laboratories.

Robolab consists of three different programming environments (modes):

Pilot is the easiest programming mode (Figure 3). Pilot programs are serial programs created using a combination of a few common functions. Pilot programs have the benefit that they will always compile and execute (although, they may not accomplish the desired task).

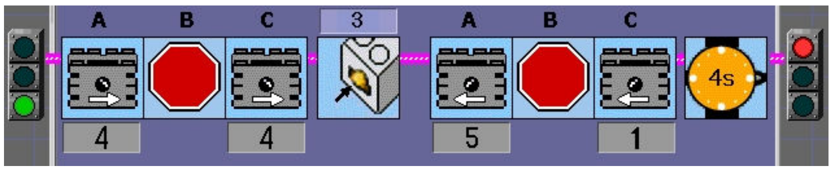


Figure 3: Sample Pilot mode program.

Inventor is the second programming mode (Figure 4). Program icons are "wired" together to create a program. Programs created can contain all the typical programming elements such as constants, variables, loops and functions.

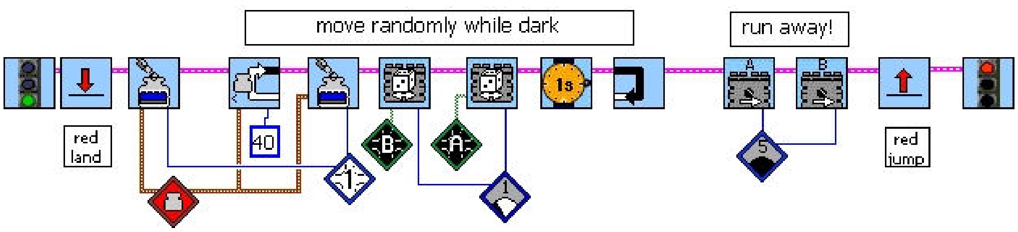


Figure 4: Sample Inventor mode program.

Investigator is the final, most capable, programming mode (Figure 5). All of the features in Inventor mode are included along with the added feature of data logging and advanced data analysis.

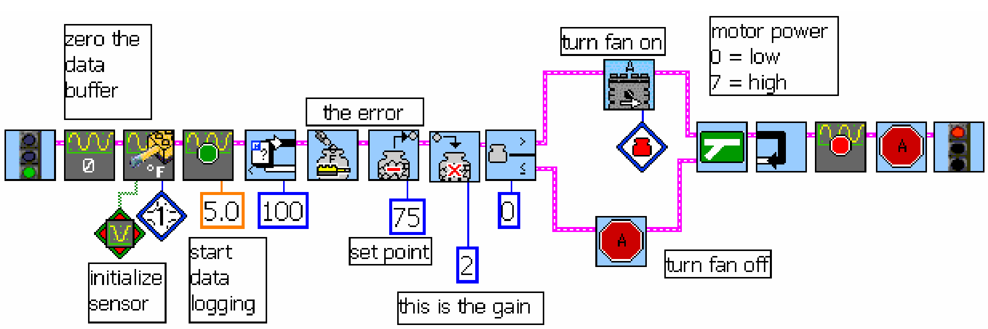


Figure 5: Sample Investigator mode program.

3. Sample Engineering Experiments

As mentioned previously, the experiments described here all include the use of the RCX programmable brick. Our aim is to demonstrate a variety of possible experiments rather than discussing the details of implementation in a particular course. More examples and programming help can be found online [30].

<u>Data collection and analysis</u>

Manual data collection and analysis is often one of the first laboratory exercises an engineering undergraduate performs. In this case, students build a vehicle that moves forward for a specific amount of time. By varying the time, students manually collect data and graph the distance traveled as a function of time. Student use linear regression to determine the "best fit" equation. All experiment design, data collection and graphing is done as homework.

In class, a competition is held to see who can make their vehicle get the closest to a prescribed distance, which is not known to students before class. Students use their graph to determine how long to turn the motor(s) on. This rather simple exercise can be used to teach interpolation, extrapolation, linear regression, repeatability, resolution, and the concept of calibration [18, 20].

Figure 6 shows one of the more creative vehicles built, a typical program, and a typical set of student data plotted in Excel. Because the programming is so simple, the focus is on the data collection and analysis, not programming. The entire exercise, including programming instructions and in-class competition, can be completed in 1 hour, spread over 2 lecture periods.

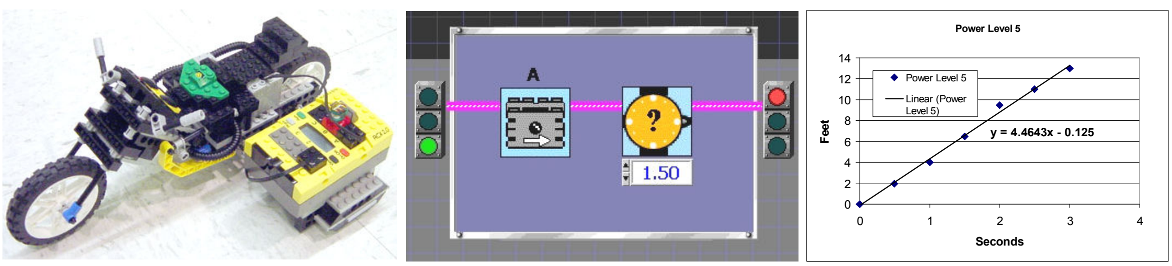


Figure 6. Sample vehicle, program, and data collected. The program shown turns on Motor A for 1.5 seconds.

One can also run a number of small experiments to teach the basics of digital sampling. Using the light sensor to estimate the blink rate of a flashing light clearly demonstrates aliasing, for instance. If they sample too slowly, they will miss a blink. Students estimating the average room temperature quickly learn to sample for long times to accurately predict the average. These experiments can also be used to teach some basic statistics, such as moments, probability distributions, and confidence levels. We have also used these small experiments to teach measurement uncertainty and repeatability. How well can they replicate their data?

Applicable courses for this experiment include experimental methods (i.e. an introductory laboratory course) and statistics. After the experiment the students should be able to perform manual data collection, calculate the best fit curve using linear regression, and be able to extrapolate/interpolate data.

<u>Natural frequency measurement</u>
One of the most common experiments in dynamics is the measurement of the natural frequency of a vibratory system. Rogers and Portsmore [20] describe an experiment in which students measure the natural frequency of a longitudinal extension spring in order to determine the spring constant. A similar experiment that actually uses the same program can be used to measure the natural frequency of a pendulum. Students are asked to make a pendulum using the RCX as the pendulum mass and record light sensor data as the pendulum swings back and forth over a black line. The entire experiment is assigned as homework with no laboratory equipment or instructor supervision required. In less than an hour at home, students can investigate how both the pendulum length and mass affect the natural frequency.

Typically students suspend the RCX from a doorway or desk using string. However, as shown in Figure 7 some students are more ambitious than others. Figure 7 also shows a typical Investigator mode program and typical data collected. Again, the emphasis is on the data collection and analysis, not equipment setup and programming.

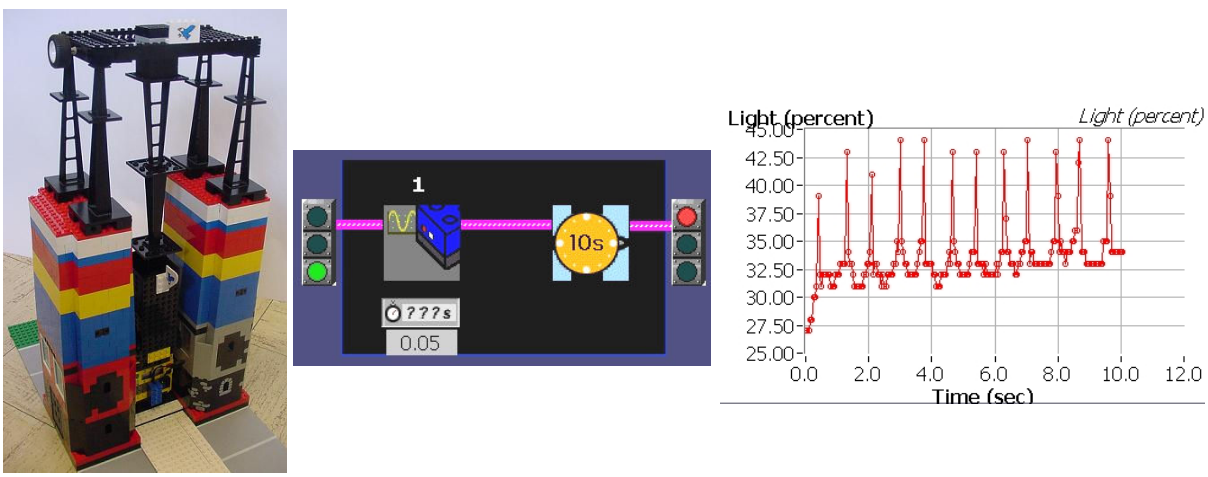


Figure 7. Sample pendulum, data acquisition program, and sample data. The program shown records light sensor readings every 0.05 seconds for 10 seconds.

Additional learning objectives may include conservation of energy, sampling theory, and Fourier analysis. For example, by also incorporating an angular rotation sensor, additional aspects of dynamics and Newton's laws of motion, such as the conservation of kinetic and potential energy, can be investigated. Fourier analysis can also be introduced quite easily. Figure 8 shows an Investigator mode program to take the FFT of a data set and the resulting power spectrum (for the data set shown in Figure 7). Many advanced data processing tools (such as the FFT) are integrated directly into the Robolab software. More advanced students can add the appropriate windows to improve the resulting Fourier transform. Again, the emphasis at this point is on the physics, with the software side limited to a few mouse clicks.

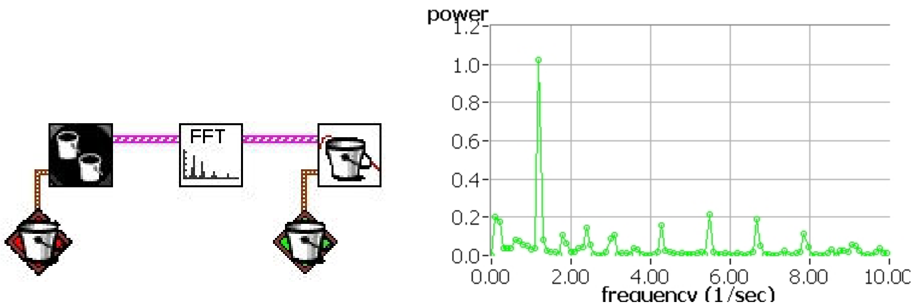


Figure 8. Program for taking the FFT and the resulting power spectrum.

The most applicable courses are physics, dynamics, or a basic experimentation course. The learning objectives include the abilities to collect data, extract information from a data set, describe how sampling rate affects the estimated natural frequency, derive the equation that describes the motion of a pendulum, calculate the Earth's gravitational acceleration, and to identify the natural frequency of a system using a PSD.

Friction

In order to measure the frictional coefficient of a car, one can build a small car with an angle sensor mounted on one of the axles (figure 9). If the RCX samples the axle's angle sensor as the car is pushed and released, one can see the initial impulse and then the constant deceleration due to friction. The program would be identical to the one shown in Figure 7 except the rotation sensor would replace the light sensor. This lab is particularly useful to teach students issues of differentiating data and poor sampling rates. Figure 9 shows a single position data set sampled at 10 Hz. One can differentiate this data twice to estimate the constant deceleration due to friction and from that, (and knowing the mass of the RCX) estimate the frictional coefficient of the plastic axle. The sample acceleration data shown in Figure 9 shows the initial impulse followed by a period of deceleration.

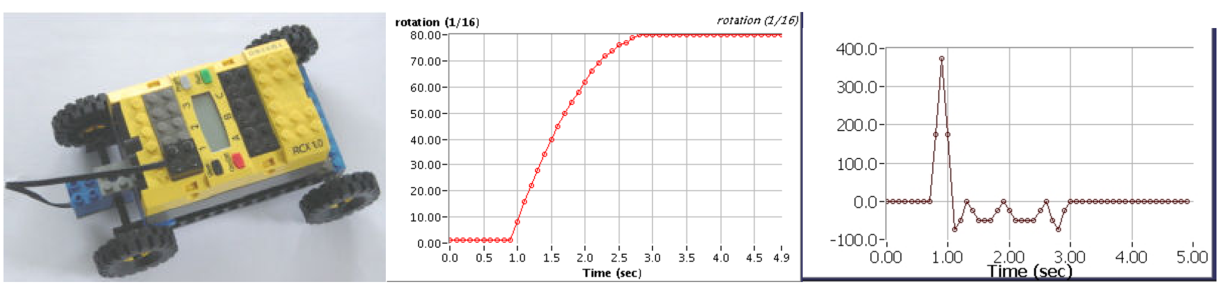


Figure 9. A sample car (left) with the corresponding position (center) and acceleration data (right).

The most applicable courses for this experiment are statics and dynamics, but this could also be used in a numerical methods course if the derivatives were performed by the students instead of Robolab. The learning objectives would include the ability to collect data, calculate coefficient of friction, perform numerical differentiation, and describe the effect of sampling rate on numerical derivates.

Characterizing Motor Performance

Determining the relationship between torque and angular velocity for a motor is another common mechanical engineering experiment typically performed on automotive or large electrical motors. However, if the learning objective is to measure the torque-RPM curve and plot the resulting power-RPM characteristic performance curve, then a LEGO® motor is entirely suitable.

In Figure 10, a simple experimental set-up is shown in which a LEGO® motor is used to lift a known mass by spooling string onto a wheel hub. By measuring the diameter of the hub, the applied toque can be calculated. Using a rotation sensor, which measures in 16ths of a rotation, the program displays the time, in tenths of a second, required to complete 10 full revolutions on the LCD of the RCX. A typical set of student data is also shown in Figure 10.

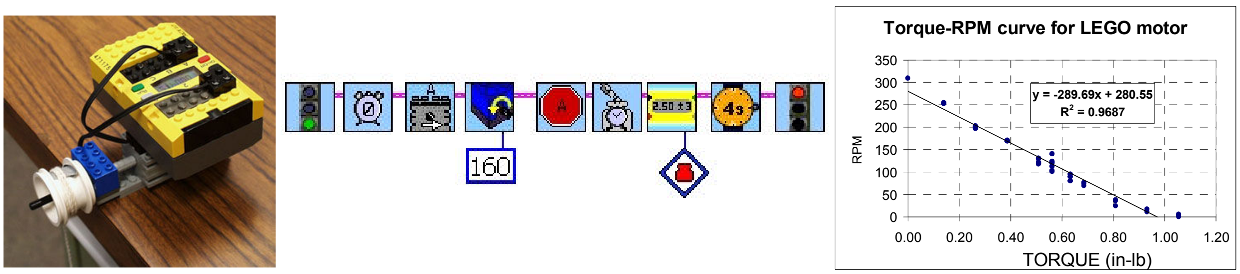


Figure 10. Measuring the torque-RPM relationship of a LEGO® motor. The program resets the timer, turns on Motor A for 10 rotations, turns off Motor A, stores and displays the timer reading for 4 seconds.

If a rotation sensor is not available or if frequency analysis is also a learning objective, then a light sensor and a black/white rotating disc can be used to collect rotation data and then the same FFT program shown in Figure 8 can be used to determine the angular velocity.

Applicable courses might include vehicle systems, mechatronics, robotics, or introductory experimentation courses. The learning objectives include the ability to write a simple linear program, collect data, perform a linear regression, and calculate power as a function of angular velocity.

Pipe Friction (fluid dynamics)

Portsmore *et al*. [19] describe a fluid dynamics experiment in which pipe friction was calculated using a graduated cylinder, a light sensor and a piece of Styrofoam. Water flows from a plenum, through a valve, through a pipe and into a graduated cylinder. After the cylinder fills to a pre-defined level, the light sensor detects the Styrofoam float, shuts the valve, and measures the time. The program is very similar to the one shown in Figure 10, only a light sensor would replace the rotation sensor and motor A would be used to open and close the valve. From this, the student can calculate the flow rate and pressure drop. The student can then use different diameter pipes and compare his results with a Moody chart. This is an example of how the RCX can be used as a low cost data acquisition system in conjunction with standard laboratory equipment.

Fluid dynamics or the associate laboratory course would be the most applicable place for this experiment. The learning objectives would include the ability to write a simple linear program, collect data, and calculate pipe friction.

Numerical methods

The objective of this experiment was for students to write a numerical integration program and compare the accuracy of various integration methods. To make the problem interesting, the data set provided was acceleration data from a low cost tri-axial accelerometer. Powered via standard 9V battery, the accelerometer outputs ±2V, which can easily be recorded on the RCX (a connector was made by cutting a LEGO® wire lead and soldering a standard connector to it).

Students had to write a simple data acquisition program, similar to the one shown in Figure 7, in addition to the numerical integration programs. The instructor held the accelerometer in his hand and "wrote" a short word on top of a large desk. Students were then asked to determine what the instructor "wrote" by integrating the signal twice with respect to time. Students had to deal with poor sampling rates and low signal levels if the instructor "wrote" slowly. However, because letters are not arbitrary shapes, complete words could be deciphered quite easily.

This experiment can be used in either a numerical methods or a dynamics course. The learning objectives include the ability to write a numerical integration program, collect data, perform sensor calibration, describe the effect of sampling rate on integration results, and to describe how the signal to noise ratio affects the accuracy of the results.

Force Transducers (Strength of Materials)

There are a variety of methods for building a LEGO® force transducer. The LEGO® light sensor is actually a very good proximity detector if one is careful to shield it from all ambient light. Using springs or even rubber bands, students can build a reasonably accurate force transducer. Students can calibrate their force transducer using either dead weights or another calibrated transducer. The downside is that sensor has a very limited resolution because the light sensor typically only has a dynamic range of 20-40 light levels at best. There are, however, third party proximity detectors (e.g. [27]) which cost around $40 that can be used to make very accurate force transducers.

Another method of building a force transducer is shown in Figure 11. This method utilizes a rotation sensor, a rack and pinion, and several rubber bands (a 5:1 gear ratio is used to increase the resolution of the rotation sensor). Again, students must first calibrate the force transducer to determine force as a function of rotation. Note that the calibration tends to be both non-linear and hysteretic due to frictional effects. However, for simple unidirectional tension tests, this does not distract greatly from the accuracy of the results.

In this example, the force required to separate a pair of 2x2 bricks was measured. When separation occurs, the system "springs" apart too quickly for the rotation sensor to resolve, which is clearly shown in the raw data, Figure 11.

Extensions to this experiment might include demonstrations of the differences between force and stress (by pulling apart different sized bricks), explorations of Newton's laws of motion and fundamental aspects of mechanics through experiments with devices such as lever arms, and the relationship between force and torque.

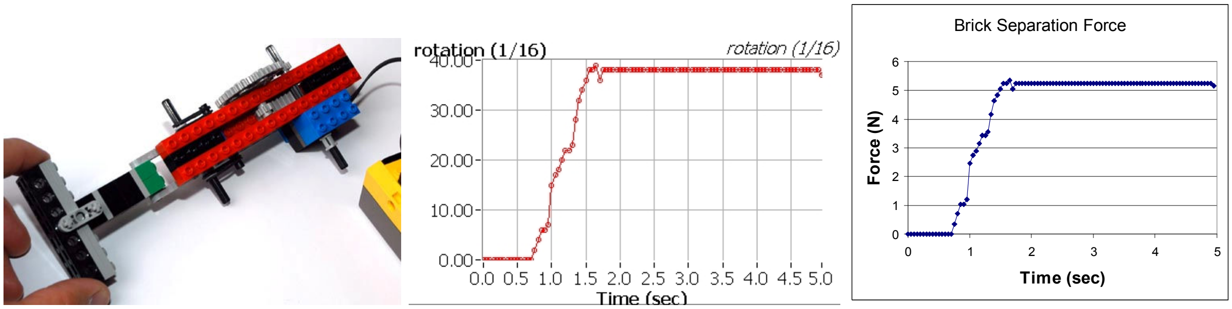


Figure 11. Rotation sensor-based force transducer, sample raw data, and calibrated curve.

A motor can be used to indirectly measure torque. Knowing the torque-RPM relationship for a motor, it becomes straight forward to measure angular velocity using either a rotation or light sensor and then deduce the torque being produced by the motor.

A force transducer can be used for a wide variety of experiments. Students need not test interlocking bricks. They can perform bending and or torsion tests (generating a stress-strain diagram) on a variety of materials (toothpicks, chicken bones, etc). One could also make a simple digital scale.

A force transducer can be used in a variety of courses, including strength of materials, statics, dynamics, and physics. The specific learning objectives would depend on what the instructor wanted the students to do with the force transducer.

<u>Feedback control</u>

Often computer simulations are used in place of physical laboratories to teach students about feedback control. If conducted at all, feedback control experiments are typically conducted at the junior or senior-level. However, the basic concept of feedback control is quite easily understood, even by freshmen, when presented in the guise of a familiar experience.

Bang-bang feedback controllers are found in many systems familiar to freshmen, such as the thermostat in their house. However, few students realize until it is pointed out, that the classic line following algorithm is essentially a bang-bang control algorithm: turn one way when you are on the line, turn the other way when you are off the line.

Levien and Rochefort [22] describe a freshmen chemical engineering experiment in which the RCX, a motor, and a temperature sensor are used as a temperature controller for Styrofoam "hot box." While the program and control method were not specified in their paper, a simple bang-bang controller would be easy for students to implement. Alternatively, the program shown earlier in Figure 5 could also be used to teach basic proportional control for such an experiment.

Two additional feedback control experiments using the RCX can be found in the literature. Brockman *et al.* [21] describe another feedback control experiment in which first year engineering students conduct a process control experiment to maintain a specified pH of a mixture using the RCX as the controller. Moor *et al.* [23] describe a more general process control experiment where the RCX is used as a computer interface. Both studies are examples of the RCX being used as a low-cost controller in conjunction with traditional laboratory equipment.

A somewhat mechanically simpler example of feedback control can easily be accomplished with a simple car and a flashlight. The basic concept is quite simple for students to understand: if it is too bright, back up; if it is too dark, drive forward. From there it is not too difficult to communicate the concept of proportional control, where we also require that the motor output be proportional to the error.

The car shown in Figure 12 has less than ten pieces and can be built in just a few minutes, regardless of prior LEGO® experience (or lack thereof). Different size drive wheels, mass of the car, and the type of flooring (e.g. carpet or tile) all affect the effective inertia of the system and can also be investigated by students.

The program shown is almost completely linear in structure and, thus, easy to write. In this case, the students were also required to record the light sensor data for data analysis. The resulting light sensor data is shown in Figure 13 for three different gains. The data demonstrates classical overshoot, settling time, and instability control characteristics.

With very little instruction, students can build the car, write the program, and conduct the experiments at home. In the context of a control systems course, this experiment takes very little time away from the traditional lecture, yet helps students build an intuitive understanding for the behavior of feedback control systems.

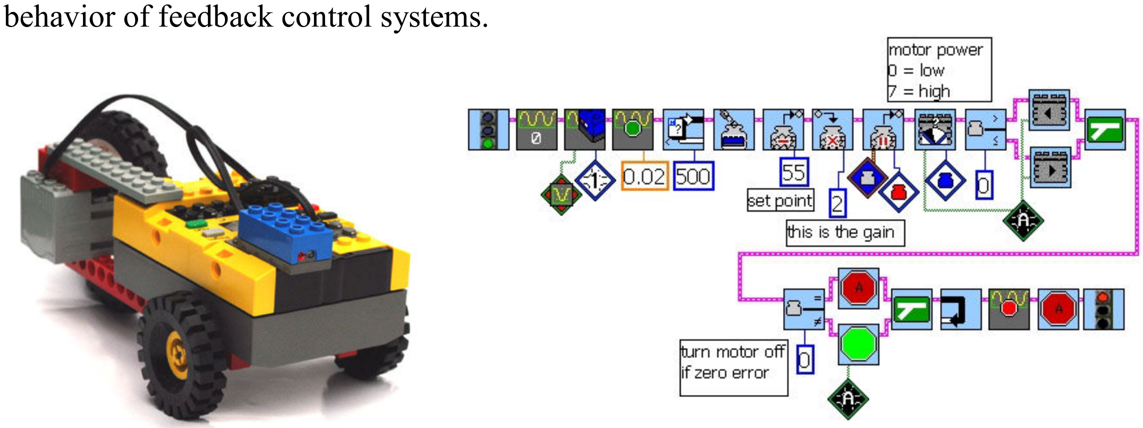


Figure 12. A very simple car and a nearly linear program can be used to investigate proportional feedback control.

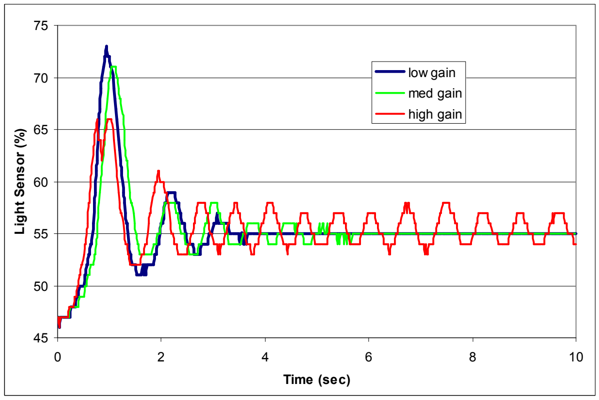


Figure 13. Light sensor readings for 3 different gains. Overshoot, settling time and instability are all evident.

This experiment would be applicable in courses such as control theory and systems dynamics, although we have used it extensively with freshmen to introduce the concept of feedback control. The main learning objectives are to be able to write a proportional control program, collect data, and describe the effect of gain on rise time, overshoot and settling time.

<u>Personal Science</u>
Resnick *et al*. [31] pointed out:

> *"…the Programmable Brick will make possible new types of science experiments, in which children investigate everyday phenomena in their lives (both in and out of the classroom)."*

While this was written in the context of K-12 education, the same sentiment holds true for undergraduate engineering. The RCX programmable brick makes personal science possible. For instance, one student can wear an RCX recording temperature. Other students can look at the temperatures measured and try to deduce where the student has been. Students have used the RCX to monitor the usage of their dorm room lights over the course of a 24 hour period. Finally, some students have used the RCX to monitor the temperature in an incubator for raising chicken eggs.

<u>Creativity</u>
The interchangeable, modular nature of LEGO® bricks makes for flexibility in their use. This readily translates to providing students with considerable flexibility when using LEGO® bricks and programmable RCXs in design exercises. From an instructional perspective, development of open-ended design assignments that address creativity as a learning objective can easily be created. Similarly, in courses structured so that students see each other's creations perform, they gain exposure to alternative approaches to the problem and can form their own assessments of what design approaches are effective or ineffective. This process serves as an effective form of peer learning.

4. Obstacles to Adoption

Despite the many studies found in the literature, the use of LEGO® bricks at colleges and universities appears to be limited to islands of enthusiasts. In this section we try to identify and address some of the obstacles to adoption.

Students are more familiar with LEGO® bricks than the faculty
One of the biggest concerns appears to be the perception that the students know more about LEGO® bricks than the faculty. For most faculty, this is probably an accurate assumption. If the learning objective were to develop LEGO® building skills, then this would indeed present a problem. However, in most cases it is not one of the learning objectives. In our classes, we routinely use very simple models (e.g. Figure 12) to demonstrate concepts and students routinely take pride in building extremely creative robots that are far beyond our skill level (e.g. Figure 14).

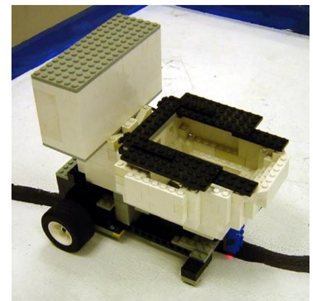


Figure 14. A creative line following "robot."

LEGO® bricks are just toys
A common perception is that you can't do "real" engineering with LEGO® bricks; or that LEGO® bricks are good for hands-on activities with first year students, but not suitable for serious engineering. Wallich [32] counters this argument with an overview of how adult engineers and researchers are using the RCX to build complex systems and do real engineering. We have used the LEGO® camera to teach a graduate-level course in image processing [33]. Student final projects sometimes included the RCX and sometimes not. For instance, one student built a system that used the camera to identify face motions and translate it into mouse movements. As a final demonstration he was able to play solitaire on the computer simply by moving his head. Another used the camera to take a picture of a scene and use the image to determine the best path for a robot to navigate through the rocks, and finally program an RCX robot and watch it drive through the field.

Finally, we have also used the RCX-RCX communication to teach distributed robotics [34]. Here, multiple robots work together to solve various problems, such as mapping terrain and playing tunes. In short, the LEGO® RCX system contains many very advanced features and capabilities that can make it an advanced-level educational tool. The attending low per-student cost (especially for robotics hardware) makes it very practical.

Faculty have to learn a new programming language
Faculty regularly require students to use software at a higher proficiency level than they themselves have. Again, this is typically the case when learning the software is not a major learning objective. In these cases, typically the teaching assistants and technicians are assigned the responsibility of teaching the software and experimental procedures.

For the cases when there is a need to have a high level of proficiency with the software, there are many choices. Faculty that already know LabVIEW will find Robolab easy to learn. Even without LabVIEW experience, Robolab is extremely simple to learn. Those that prefer C or Java can use one of the other structured or object-oriented programming environments for the RCX.

Laboratory Resource Issues

Gage and Murphy [16] present a good discussion of problems encountered during an attempt to implement the use of LEGO® bricks in a computer science course. Dealing with stolen, damaged, and missing parts is identified as a major issue. They point out that it is not uncommon to sacrifice one or more kits as a source of spare parts, which adds to the overall cost.

Typical LEGO® kits including an RCX, an assortment of sensors, motors, and enough parts to suitably build robots, cost approximately $200 (discussed more below). This cost is feasible in the context of how much students pay for textbooks, especially when students work in teams of two and can share in costs. There are both advantages and disadvantages to having students keep the kits for extended periods of time. Price *et al*. [35] describe the proposed use of the RCX for distance education, where attendance in on-campus laboratories is nearly impossible. Students will keep kits at home for successive classes over a period of time, thereby amortizing the cost of the kits over several courses.

There are four practical methods for using LEGO® kits in the college/university classroom when students are going to use the kits for an extended period of time (e.g. an entire semester):

1) Require students to purchase the kits. This method is logistically the easiest, but also can be costly for the students. Experience has shown that a market for used kits develops just as the case for used textbooks, which partly reduces the cost to the student.
2) Maintain a dedicated laboratory (or laboratory space) with all the necessary kits. This method works well for traditional laboratories using the RCX in conjunction with fixed laboratory equipment. This method is difficult if any robot construction, out-of-class, or at-home experiments are conducted.
3) Loan or rent kits to students. The university purchases and owns the kits and then either loans or rents (with deposit in each case) the kits to the students for the duration of the exercise or term. For experiments which only require the RCX and a few sensors, a "core" kit can be used quite effectively. However, for courses which involve extensive robot construction, inventorying kits at the end of term can be a major issue since some kits contain over 800 pieces.
4) Hybrid: loan/rent a "core" kit (with the more expensive parts such as the RCX and sensors) and have student purchase their own "bricks." This method works well for courses which involve robot competitions.

The most difficult scenario is for a course in which a single experiment or exercise is conducted. In this case, it is economically unfeasible to make the students purchase their kits (option 1 above) or even their own bricks (option 4). This leaves only options 2 and 3, which both require the kits to be sorted and inventoried periodically. Experience has shown that even after a single experiment the inventorying process can be very time consuming and pieces are often missing and/or damaged [16].

Kits recommended

Retail Mindstorms Kits: The advantage of these is that they can often be found at discount stores or online auctions for extremely low prices ($100 or less). As mentioned earlier, the disadvantage is the lack of an AC adapter port (Figure 1). We have found that the students will often spend more on batteries over the course of a semester than they save on the initial purchase. Rechargeable high-capacity NiMH batteries are highly recommended.

Team Challenge Kit: This kit contains over 800 pieces and costs about $200 ($225 with Robolab software). Inventorying this kit is extremely time consuming. This kit is recommended for dedicated LEGO® labs and student purchases only. Kits can be purchased with either a USB or serial IR tower. In the US it is only available from Pitsco-LEGO® Educational [36].

Robo Technology Kit: This kit is an excellent “core” kit, contains about 200 parts, and costs $149 ($189 with software). Inventorying can be made even easier, by removing all the “bricks” and leaving just the RCX, motors, lamp element, wire connectors, and sensors. Several simple experiments can be done with this kit, but robot competitions will require additional parts. Alternatively, for experiments that use the RCX as a controller (e.g. process control) or data acquisition device (e.g. pipe friction), this kit is a low-cost alternative to the Team Challenge kit.

Technology Resource Kit: For the scenario in which students rent a “core” kit and purchase their own “bricks” (option 4 above), this is the recommended kit of “bricks.” With over 1100 pieces, it is an excellent value at $55 (again, only available at Pitsco-LEGO® Educational).

Textbooks

Unlike NQC, which is well documented by Knudsen [26], Robolab did not have any textbooks associated with it. In direct response to this issue, Wang [37] published a “textbook in progress” as a workbook. The textbook is expected to be in print by the end of 2004.

Additionally, websites dealing with each of the RCX programming languages can easily be found on the Internet.

5. Conclusions

In this paper we have described several simple experiments that focus on fundamental engineering concepts. In doing so, we have shown that the RCX can be either a viable alternative to or can be used to supplement traditional engineering laboratory equipment. Use of Robolab in conjunction with the RCX has the following additional benefits:

- Allows data collection and analysis in courses early in the curriculum, where data collection may not be one of the key learning objectives.
- Graphical programming is easy to learn with no prior experience necessary.
- Students can conduct most of the experiments at home at the most convenient time for them.
- Using LEGO® bricks seems like play, which increases student time-on-task.
- Students have freedom in the design of the experiments, which both encourages cognitive development and fosters creative thinking.

Furthermore, many of the experiments can be included in traditional lecture courses. An hour invested, in place of a traditional lecture, can payoff several fold by increasing both student learning (in depth understanding and cognitive development) and interest.

Finally, whether or not students are actually learning better needs to be addressed. This is an area of research that we are currently investigating through several projects. Nonetheless, even without quantifiable data, we are positive that these experiences do not hamper student learning and, at a minimum, increase the students' enthusiasm towards learning.

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