# Learning Process Control with LEGOs®

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## Introduction

One of the key challenges of undergraduate engineering education is providing students an experience that includes both solid theoretical underpinnings and a clear connection to industrial practice. This is especially important for process control, where students often find it difficult to connect the mathematical analysis with a practical application.

Over the last 18 months, we have developed inexpensive and flexible process control lab kits that allow students to design, implement and test their own control systems in the classroom. At the heart of the process is the LEGO® RCX brick, an inexpensive system that grabs student interest. Using the kits, students are able to construct the physical process with quick release fittings and implement the control system in software using LabVIEW™ Student Edition and ROBOLAB™ for LabVIEW.

The first prototype consisted of level control for a single tank. The kit has been expanded to include level control for two tanks (interacting or noninteracting), flow control, cascade control and temperature and. The software has been modified so that a simple front panel is immediately accessible and understandable to the students, but, as they learn more process control theory, they can study, understand and modify the subpanels, which perform the control actions. The software is designed to work as a general control program for the LEGO RCX brick and will work with any sensors and control elements that can be interfaced with the RCX brick.

## Development of the Laboratory Kits

Flexible, inexpensive kits were developed which students used to quickly put together small processes and their control systems. The kits contained a pump, two tanks, and a variety of piping, fittings and sensors. The main pieces have quick release fittings[1] allowing a process, including sensors and control valves, to be assembled quickly and easily. Students connected the sensors and control valves to a computer interface and "built" a control system in software. The details of the basic kits were provided in an earlier paper[2].

**Modifications to the kit**

In the second year of the grant period, further components were built for the kit, and additional software was programmed to increase the number and types of experiments that it can perform. These are summarized below.

New Pressure Level Sensor

Our original pressure level sensor was discontinued, which required development of a new one. In addition, the original sensor did not have adequate resolution. A new sensor system was developed using a Honeywell Micro-switch 26PCAFA6G sensor and a four-wire interface to the RCX brick developed in cooperation with Pete Sevcik (www.Techno-stuff.com). The Microswitch sensor has a range of 0-1 psi. The four-wire interface has been calibrated to use the lower part of this range (approximately 0-10 inches of water) to improve the digital resolution of the level sensing. The RCX brick performs a 10 bit A to D conversion of a 0 – 5 volt input. Figure 1 shows calibration data developed by four groups of students in one class session working on four different kits. The raw reading is the decimal equivalent to the ten bit binary value resulting from the A to D conversion. You will notice that the interface operates "backwards", starting out with a high raw value and lowering as the level increases. The graph also shows the consistency and linearity of these sensors.

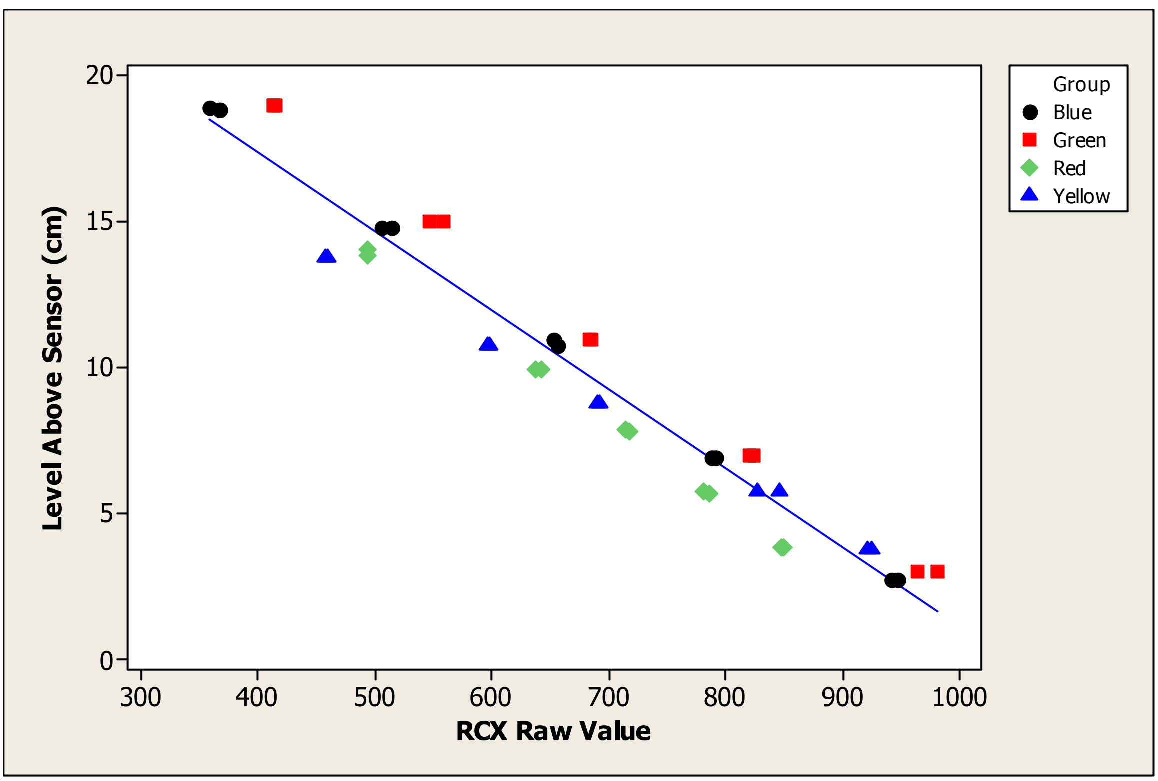


**Figure 1:** Student generated calibration curves for the new pressure sensor based on the Honeywell Micro-switch pressure sensor and a Techno-stuff four-wire interface to the RCX brick.

Orifice Meter

In order to perform flow control, an orifice meter was designed to fit inside the 3/8 inch tubing. Figure 2 is a diagram of this pressure sensor. This sensor was fabricated by taking a piece of bar stock and milling in from each end so that the 3/8 inch tubing fit inside of it. A small piece of the bar stock was left in place (0.016 inches thick), through which the orifice hole was drilled. The orifice has a diameter of 0.187 inches, with five inches of straight tubing before and after it. Two pressure tap holes were drilled in the tubing; one hole is 0.156 inches downstream of the orifice plate, and one hole approximately 0.42 inches upstream of the orifice plate. This is one tap at one-half pipe diameter downstream an the other between one and two pipe diameters upstream forming radius taps (the tubing is 0.311 in ID.) These are connected to a Micro Switch 26PCAFA6D pressure sensor. This is the differential sensor version of the sensor used for monitoring level. Two holes were drilled in the bottom side of the pressure sensor to connect to the pressure taps with small tubes. The standard pressure connections were sealed with LOCTITE 454 Instant Adhesive.

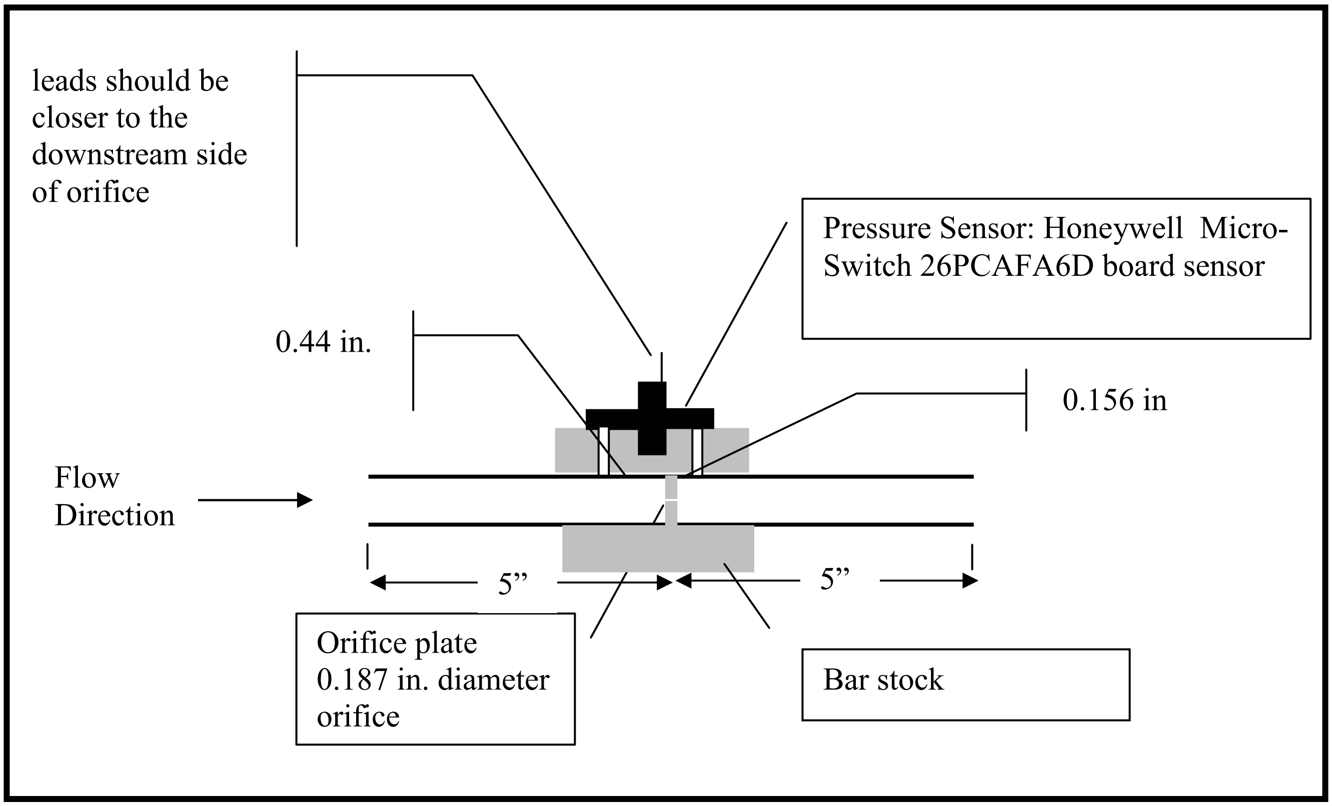


Figure 2. Diagram of the orifice meter.

The beta value for this orifice meter is approximately 0.6. Figure 3 shows initial calibration data for this orifice meter. The line on the graph is a regression fit forced through the origin. From approximately 10 ml/sec to 25 ml/sec the regression curve is very linear and will approximated by the single parameter fit. The right hand scale shows the corresponding Reynolds Numbers for this meter. These Reynolds Numbers are lower than is commonly used for orifice meters. We choose to operate at these lower numbers to minimize the pressure drop across the orifice.

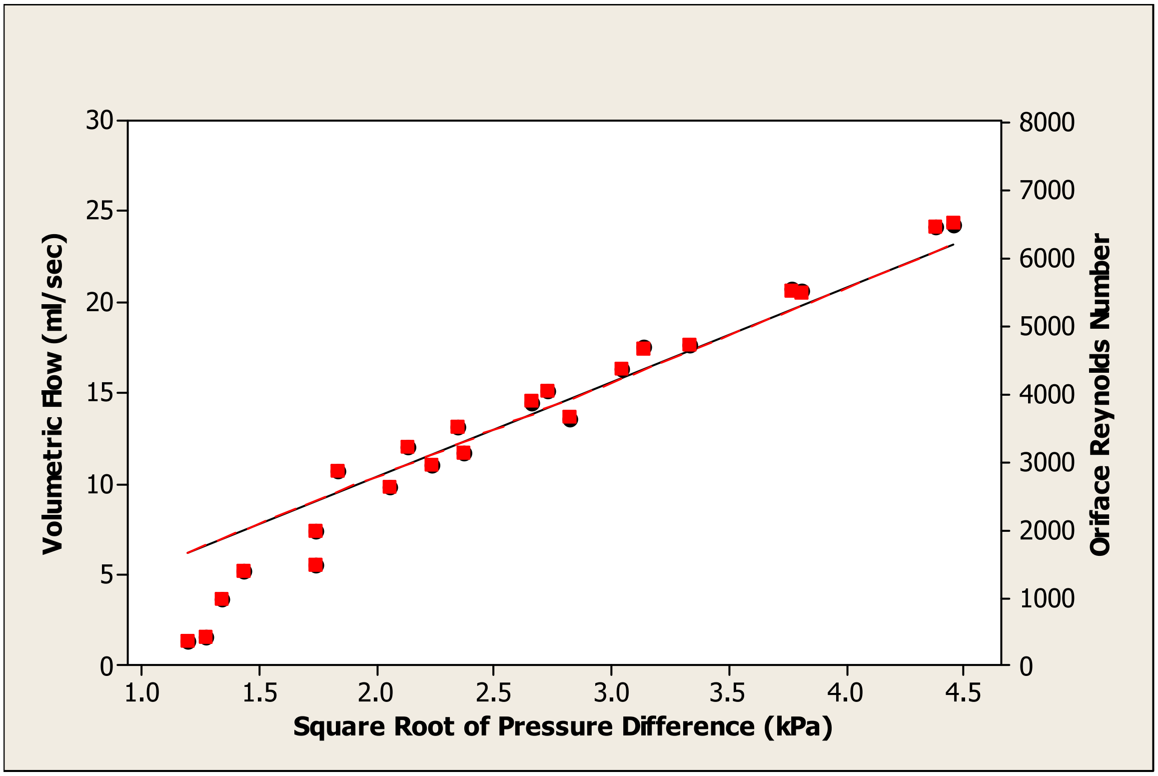


Figure 3: Calibration curve for orifice meter.

Control Valve

A new control valve assembly was designed that requires no parts machining. This configuration allows the Lego motor and the brass valve to move slightly both horizontally and vertically to provide a good connection between the two. The components and final valve are shown in Figure 4. To create this, two thin flat-top Legos are glued to the bottom of the valve (using LOCTITE 454 Instant Adhesive). The valve is attached to a Lego small baseplate (Pitsco #779279) using a 4-stud axle (#pg 112) with two 1x2 bricks with round holes (Pittsco #779928-114). The axle goes through the bricks with round holes, which are attached to the flat-top Legos on the valve. This allows the valve to tilt vertically or slide horizontally as needed to connect to the motor. The motor is attached to the baseplate using small axles and connector pegs that allow it to tilt vertically. A 4-stud axle connects the motor to the valve.

This valve configuration is easier to construct than the earlier valve[2], but it is not as robust for the students. We found that the valve baseplate should not be attached to the same baseplate as the Lego tower, because if the tubing is not exactly the same length, torque is developed and the structure may collapse. However, if the valve baseplate is allowed to move slightly to adjust for different tubing lengths, the new control valve assembly works fine.

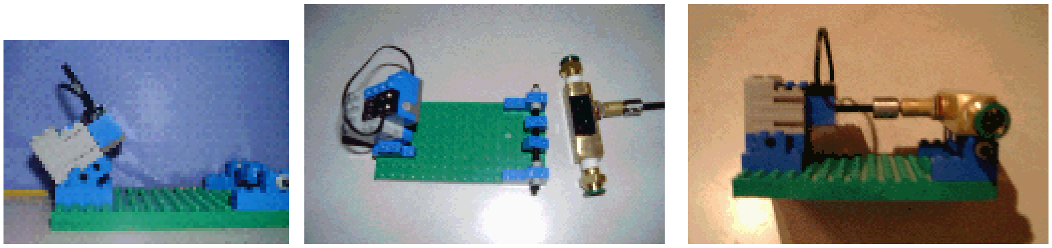

Figure 4 – Control valve assembly. The Lego motor is able to tilt vertically (left), and the control valve can tilt vertically as well as slide horizontally (center), to ensure alignment between the two pieces.

Temperature Control

An inexpensive static mixer (Cole Parmer A-04668-04 ) can be used for temperature control experiments. A "T" is attached to the mixer, and warm and ice water are mixed along the static mixer to obtain a temperature set point. The temperature can be measured with a Lego temperature sensor (Pitsco B979889). With this setup, thermal modeling can be demonstrated, and a simple temperature control loop developed and tested. Separate temperature and flow control is also possible.

Power Switch Box

A relay switch box was also constructed to control the pump power. A schematic of the box is shown in Figure 5. The box consists of a power cord, a three-prong plug for the pump or other electrical load. In side it contains a solid-state relay, three-position switch and a power indicator light. The single pole double through switch allows the user to either turn the power on, off our put it under automatic control. A resister is in parallel with the indicator light to bleed of a small leakage current from the solid state relay and prevent the indicator light from lighting with the power is not being sent to the switch box outlet. When in automatic mode the outlet is controlled by a signal from the RCX brick. The signal line from the RCX also includes a bridge rectifier circuit so the switch box is not affected by the polarity of the signal from the RCX. A parts list is shown in Table 1.

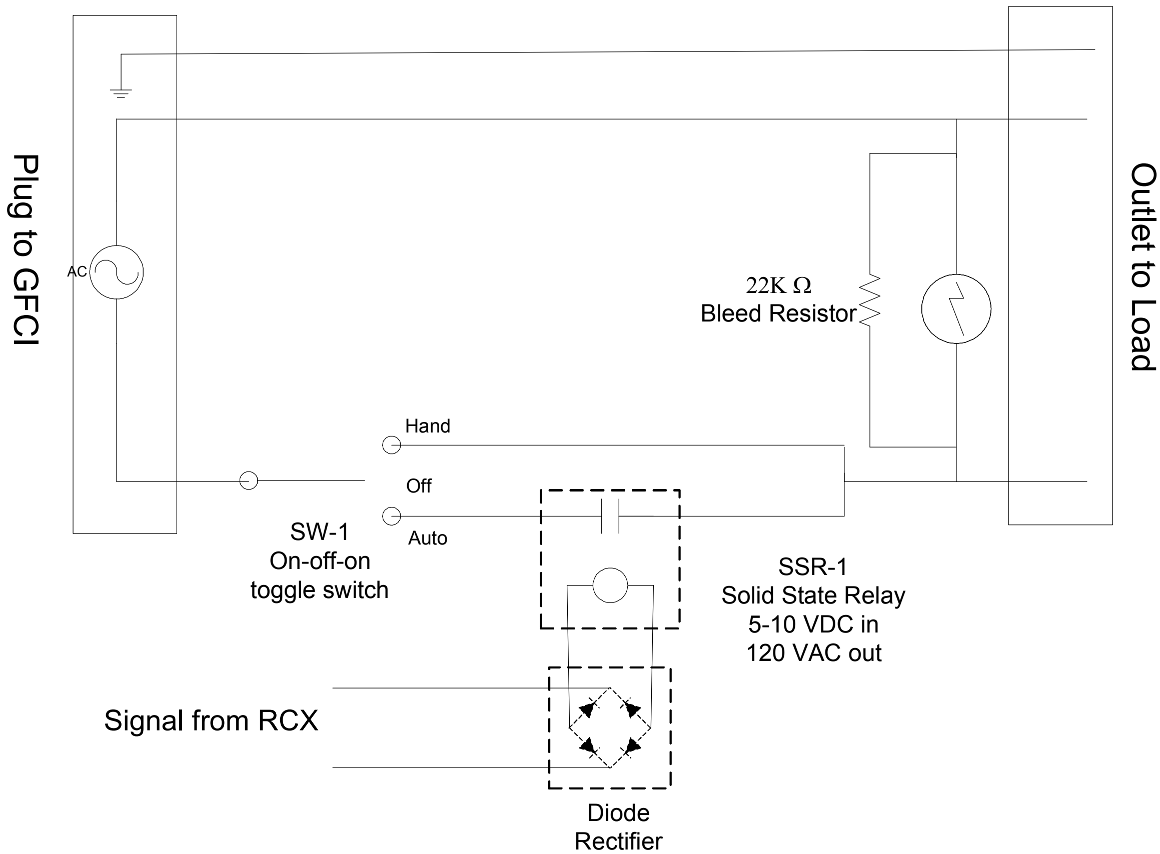


**Figure 5**: Schematic of Switch Box for controlling pump and resistance heater

| Item | Part | Mouser model # |
|---|---|---|
| 1 | Power Cord | 173-53101 |
| 2 | On-Off-On toggle switch | 633-S303T |
| 3 | Solid State Relay (SSR) | 653-G3A-205B-DC5 |
| 4 | Indicator light (Chicago Miniture) | 606-6073-001-634W |
| 5 | Three-Prong Outlet | 5160-49-8BK |
| 6 | Lego Connector | Made from one end of Lego Extension wire |
| 7 | Project Box | 563-CU745 |
| 8 | Feet | 517-SJ-5008BK |
| 9 | Cord Seal | 561-MP5P4 |
| 10 | 22K, 1 watt resistor | |
| 11 | Bridge Recitifier | |

Table 1: Parts list for Switch Box

Software enhancements

The software for the system has been extensively rewritten, using LabVIEW Student Edition 6i and RoboLab for LabVIEW 2.5 . The resulting program is a general control system for the RCX brick. It is designed to be used the previously described hardware and can also be used with any sensors or final control elements that can interface with the LEGO RCX brick. The major limitation of this software is the loop timing. It takes approximately one second to execute a loop due to the delay in communicating with the RCX brick. The exact speed is dependant on the hardware. We have run the software mainly on Pentium III and IV computers running Windows 2000. The software should be portable to Macintosh computers as well but this option has not been tested.

The improved software includes main program screen shown in Figure 6. This screen allows students to select the experiment they will be running. It also includes options for setting up the appropriate sensor definitions (active or passive) and for downloading the portion of the program that resides on the RCX brick.

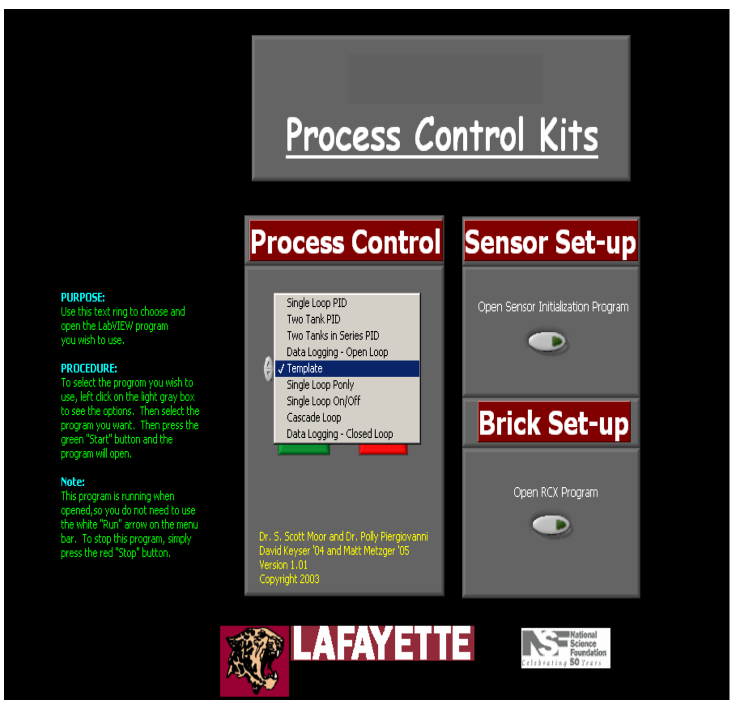


Figure 6. The opening front panel for the process control kits.

In addition, the front panel has been redesigned so that the students can quickly understand what they are seeing, even before they have learned much about process control. As an example, the front panel for a Single Loop PID loop is shown in Figure 7. The students view this screen on the first day of class, and are quickly able to observe that the yellow line shows where they want the level to be, and the red line is where the actual level is. Thus, they are immediately able to understand the concept of set point and controlled variable. As the students learn more, they can view subpanels, and find the sensor, controller and final control element, just like a block diagram (see Figure 8). They can also view the controller algorithm.

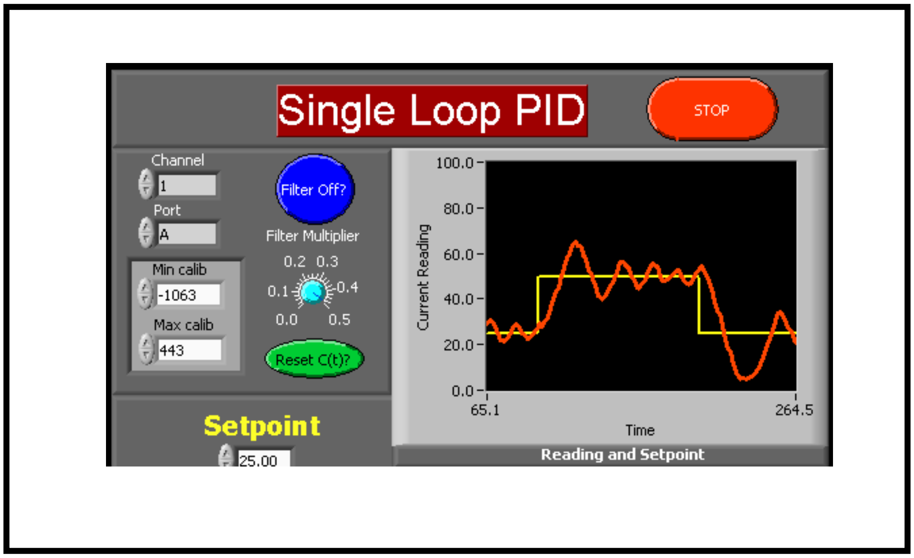


Figure 7. Front panel for Single Loop PID.

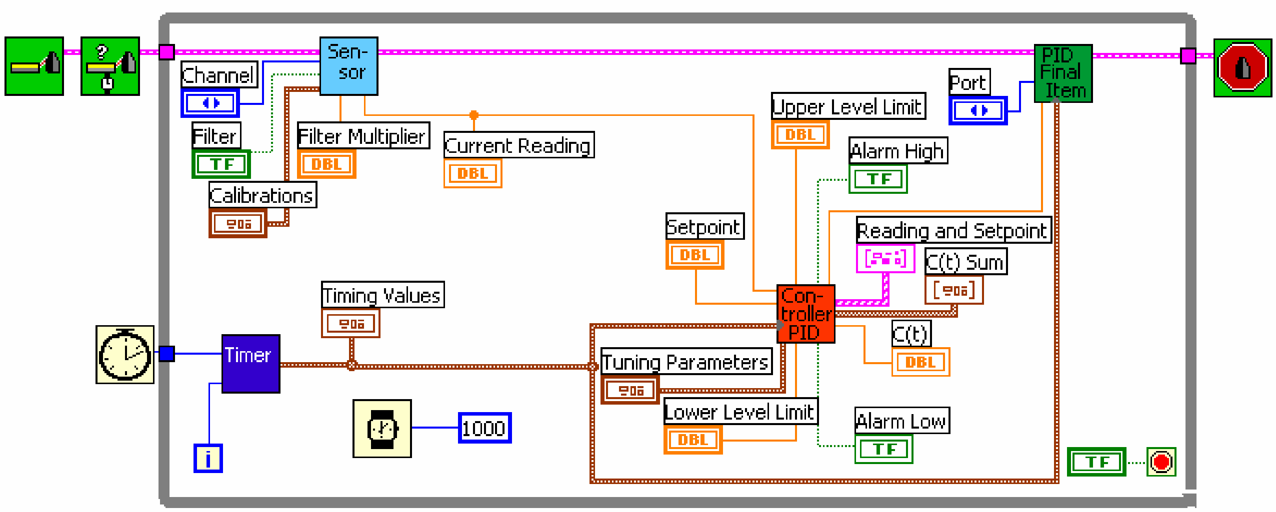


Figure 8. The VI for the single tank PID controller.

Other software developments have extended the applications of the kit. On/off level control has been written for either one or two tanks. There are also "High Level" alarms that can be linked to the on/off control and turn off the pump if the tank is going to overflow. Software has been developed to measure the valve coefficient ($C_v$), and do simple flow control. In addition, both flow and level control can be applied to a single tank either as two independent loops or as cascade control. With the current software, the experiments listed in Table 2 can be performed. We have also added the capability to do sequence control (programmable logic control). There is an example sequence control that fills a tank and heats the solution using an aquarium heater. It is simple for students to modify the sequence control using LabVIEW icons representing standard logic statements (and, or , not …).

| Set Up | Experiment |
|---|---|
| Single Tank – Level Control | First Order Dynamics |
| | P-Only Control |
| | Level Control - PID |
| | Controller Tuning |
| | Level Control – on/off |
| Two Tanks | Parallel – Interacting Level Control |
| | Series – NonInteracting |
| Flow Control | Measure Valve Coefficient ($C_v$) |
| | Simple Flow Control |
| | Controller Tuning |
| Single Tank –Flow and Level Control | Two Independent Loops |
| | Cascade Control |
| Experiments still being tested: | |
| Static Mixer – Temperature Control Only | Thermal Modeling |
| | Simple Control Loop |
| Static Mixer – Multi-variable Control | Separate Flow and Temp. Control |

Table 2. List of experiments that can be done using the current process control kit.

The basic sub-VIs (sub programs represented by icons in the LabVIEW programming environment) used in developing the various standard experiments are also included in a palette readily accessible to students. These sub-VIs include sensor, square root extractor, PID controller, P-only controller, On/Off controller, final control element, graphing and timing. With these sub-VI students can easily complete open-ended projects designing their own control systems. In fact a student doing a class project created the sequence control example.

**Results**

The LEGO kits were used in the classroom for the second time during the Fall 2003 semester. Twenty-seven junior and senior students were enrolled in two sections of the course. On the first day of class, the students assembled the kits in groups of three or four. They were walked through the procedure to set up level control for one tank, and then allowed to make different changes to their system (set point change, disturbances, control parameters). After the students had worked with the kits for a while, the class discussed several process control terms (controlled variable, manipulated variable, set point, disturbance, etc.) and defined them according to the system they had in front of them. The students observed that control can be "good" or "bad", depending on some parameters they chose to input into the software. They were able to understand the purpose of process control, and imagine why it was important for chemical engineers.

In later classes, the students used the Lego kits to observe the first order response of the LEGO temperature probe, and measure its time constant (10 seconds), learn PID control and to observe and practice control parameter tuning techniques. The kits were used in an inductive way, observing the effects of changes before the explanation was provided, as we have found this to be an effective way of teaching[3,4].

During the last week of classes, the students filled out an anonymous "Lego Kit Survey", so we could judge the effectiveness of the kits. First, the students answered four questions concerning the kits. A content analysis of their answers to these questions is shown in Table 3.

We found that the students did like the way the kits linked the abstract math and theory to the concrete example of the kits, and they found the kits were fun. They indicated that they were able to better understand the concepts presented in class. They also had suggestions for improvement, some of which have already been implemented. For example, we have a smaller tank available which has a time constant half the length of the tank these students used (4 minutes instead of 8 minutes). Also, the flow sensor and thermal sensor were not working in time for this group of students, so they were not able to work with all of the experiments now available.

| **Categories** | **Number of Comments** |
|---|---|
| **1. What do you remember about using the kits?** | |
| Linking math and theory to practice | 5 |
| Being able to **see** the control loop | 4 |
| They were fun and interesting | 4 |
| Seeing the control valve adjust after a set point change | 3 |
| They helped understand the objective of the class | 2 |
| The kits were messy | 3 |
| The process was slow | 1 |
| | |
| **2. What do you see as the purpose of the Lego kits in the class?** | |
| As a hands on example of complex material | 9 |
| To relate abstract theory to concrete example | 8 |
| Relate the process to the graphs (showing current level) | 3 |
| To see the effects of disturbances and changing parameters | 2 |
| To have experience setting up an actual system | 1 |
| | |
| **3. What was most helpful about using the kits?** | |
| Seeing the controller in action | 4 |
| Seeing the effects of set point changes, disturbances and parameters | 4 |

| | |
|---|---|
| Understanding the initial concepts | 3 |
| Since they were fun, we could concentrate more | 3 |
| Seeing the pieces of the process (sensor, controller, valve) | 3 |
| Uncertain | 2 |
| | |
| **What improvements would you like to see in the kits or their use?** | |
| More than just a draining tank | 6 |
| Use the kits more, especially after theory | 5 |
| Have a chance to alter the PID equation, and see the effect | 1 |
| More structure to the workshops | 1 |

Table 3. Content analysis of survey questions

In addition to the four open-ended questions, the students answered five questions about the kits using a Likert scale, where a 1 indicates that the student strongly disagrees with the statement and a 5 indicates that the student strongly agrees with the statement. The wording of the statements was such that "agreeing" with all the statements was not always the positive answer, so the students had to respond with thought. A graph of the results is shown in Figure 9. For this figure, the survey questions were rewritten so that they are positive, so the results are easier to interpret.

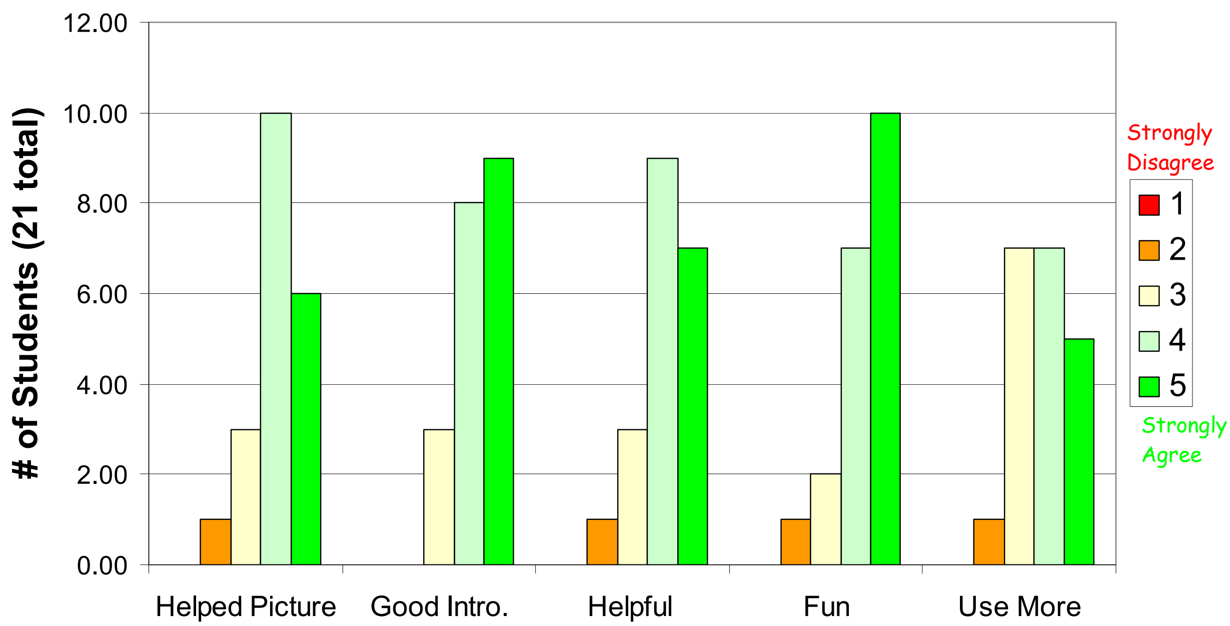


Figure 9. Response to the survey questions. The questions were as follows:
"The Lego kits helped me picture what was happening in class."
"Remembering back to the first week, the kits provided a good introduction to the subject."
"I found the kits to be very helpful."
"The kits were fun to use."
"I wish we could have used the kits more."

**Conclusions:**

Lego flexible process control kits have been expanded and improved to provide more hands-one experience for students. The students found the kits to be "fun", and helpful to understand the abstract concepts of process control. The kits "showed how control is a dynamic process, even when you aren't changing the set point".

**Acknowledgement**:
This material is based upon work supported by the National Science Foundation under Grant No. 0127231. Any opinions, findings and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

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