Session 1526

Design – Build – Test:
Flexible Process Control Kits for the Classroom

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Abstract

Traditional undergraduate instruction in process control focuses on abstract analysis and often does not prepare students for the industrially important task of synthesizing process control strategies and designs. This project bridges the chasm between academics and industry by developing inexpensive and flexible process control lab kits that will allow students to design, implement and test their own control systems. 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 ROBOLAB™ for LabVIEW™.

Inexpensive kits were developed using LEGO components that include a tank, sensors, motorized control valve and a control algorithm. The kits are easy to reproduce. With them, students conduct several level experiments which illustrate concepts of simple draining tank dynamics. The students plan and construct the piping, determine the placement of sensors and control elements and decide the process control parameters. In a single class period, the students design, construct and test their process.

Because the kits are inherently safe and require only electrical power and water to run, they can be used for laboratories, classroom demonstrations and exercises, independent activities and for educational outreach to high school students.

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. Nowhere is this felt more acutely than in process control. Students often have difficulty connecting the analysis they learn to the practical application of process control, resulting in low student interest in the subject. They are often not prepared for entry-level tasks of synthesizing control strategies including the basic task of placing sensors and control elements. They know analysis but not synthesis and do not have a full appreciation for the importance of dynamics in real processes.

Background/Current Practice

Currently process control focuses primarily on analysis using frequency analysis techniques, (e.g. Laplace transform analysis). Stephanopolous suggests that in process control instruction we are “preoccupied with the analytical leg” of process control largely because we do not know how to teach the other issues involved in the synthesis of a process control system.[1] Important control system synthesis skills which students need include: defining specific operational objectives for the controls system from broader product and process needs, conceiving of possible control structures, selecting sensor and control element locations in the process, choosing among alternative structures, understanding control in a multivariable environment (i.e., able to develop Multiple Input/Multiple Output, MIMO, control systems), and designing appropriate safety and override systems.

Maintaining student interest in process control is challenging. Lant & Newell note that most students find process control conceptually difficult, perceive it as peripheral and have trouble integrating it with other material. As a result they “find it more of a chore than fun to learn.”[2]

The attempts to answer these practical problems in process control education have been addressed using three broad approaches: (1) computer simulations, (2) laboratory experiences and (3) case studies.

A number of authors have reported on their use of simulations to assist in process control education.[3, 4, 5, 6] One very creative option is a simulator game developed by Woo.[7] Rhinehart, et. al. describe a fairly thorough approach using a flash drum as an example that does include control system synthesis and realistic issues such as statistical noise in the system.[6] We have used the process control simulation software Control Station for a number of years in our current process control course.[3] This software, like many of the other simulation approaches, helps students connect their analysis with real processes. However, in most of these programs the simulated control systems used are already set up and offer students little insight into the control system synthesis.

Bequette suggests that laboratories may be the most important experiences we give our students in a process control class.[8] Most process control courses use some form of laboratory to supplement the lecture material and several have been described in the literature.[9, 10, 11] In most of these laboratories the control system synthesis is substantially complete so again the student experience is necessarily limited. Even in the most flexible of these systems the sensors and control valves are already piped in place for the student. We also have used some laboratory experience with our process control course. In some cases we have encouraged students to build their own level control system. These projects have been excellent learning experiences for our students but they have been limited to one simple loop and to control approaches that students could implement cheaply and easily (i.e., in most cases, simple on-off control).

A few authors mention the use of case studies or design projects.[2, 12] Rinehart’s approach, mentioned earlier, is really a combination of simulation with a case study project.[6] In our process control course we have had a major distillation control system design that was a combined project with our unit operations class. This approach has given our students a good initial try at control system synthesis; however, it lacks the feedback of actually building and testing the control system.

One problem, which many authors note, is the difficulty of incorporating all the material we might like into the undergraduate process control courses.[8, 13] In particular, the explosion of inexpensive digital computing has added importance to discrete as well as continuous control algorithms while opening the way for easy and inexpensive implementation of much more advanced control strategies. Because of these advances, process control practices are constantly changing and more diverse than in the past. To accommodate the changes in industrial practice and in our understanding of what issues must be taught, it is crucial that new laboratories in process control be flexible enough to accommodate a wide range of control structures and algorithms.

In this project we addressed this problem by developing a laboratory kit that allowed students to go through all the steps of synthesizing a control system. Students assembled the process they were controlling, including placing sensors and control valves, using a collection of process units, pipes and fittings that have simple quick release connectors. Then they interfaced the process instruments to a computer where they "built" the control system in software.

To accomplish these student learning goals, the laboratory kits should be an inexpensive flexible system that:

1. can easily be used for open-ended projects
2. are inexpensive enough that multiple setups can be easily purchased
3. are portable
4. require only standard power and water so setups can be used outside of a traditional laboratory facility
5. can be used as a lecture demonstration or active learning exercise in a regular class session
6. are simple and safe enough to be used by unsupervised students for out of class assignments
7. allow for application to various other engineering classes in the future (i.e. Introduction to Engineering, Material and Energy Balances, Fluid Mechanics, Unit Operations and/or Reactor Design).

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 variety of tanks, pumps, piping, fittings and sensors. The main pieces have quick release fittings 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 "build" a control system in software. With this set up, virtually any control system structure and algorithm could be implemented. Building both the process and the control logic allows for full synthesis and testing of the process control approach. The flexibility of the computer-based control allows for the implementation of almost any desired control structures and algorithms.

<u>Computer Interface</u>

The computer interface is LEGO® RCX® brick, an inexpensive system that grabs student interest. This brick contains a Hitachi microprocessor with three A/D inputs (0-5 volts, 10 bit) and three outputs (0-5 volts, pulse width modulated) and is part of LEGO's Mindstorm Robotics

Invention System. The brick can communicate with a personal computer through an infrared link. LEGO and third party vendors have an array of sensors available including touch, light, sound, and temperature sensors. LEGO also has a number of motors that can be controlled by the RCX brick.

Sensors and Interface

Passive and powered sensors for the RCX can be made with a minimal understanding of electronics[14]. Sensors were developed for liquid level, flow and pressure. A pressure sensor with a range of –50 mmHg to +50 mm Hg was obtained from Omega Electronics (Stamford, CT).

There are two issues that make using non-LEGO sensors difficult. First, LEGO's active sensor interface is difficult because it multiplexes power on the same two wires that it senses data. In addition, the LEGO bump connector is not polarized, so the ground wire is not known in advance. To address these problems, an interface for powered sensors was purchased from Techno-stuff.com[15]. This brick converts LEGO's two-wire output to a three-wire output (ground, source and input), and has a diode bridge to solve the polarity problem. The converter brick provides regulated 5 V power to drive the powered sensor. It also provides a linear mapping of the input voltage to the value read by the program. The converter brick is made from a LEGO brick and can snap onto any LEGO. One side has three pins: + 5V, ground and input. The sensor draws power from the 5V pin, while it puts a signal between 0 and 5 V on the input pin. The input voltage is read by the program as a value between 0 and 1023.

Control Valve

The control valve is a LEGO gear motor attached to a needle valve (see Figure 1). The linkage is via a LEGO plus-shaped shaft, a LEGO rotation sensor and a simple coupling. The rotation sensor has a plus-shape hole in it and allows the shaft to move horizontally as the valve stem moves in and out. The plus shaft is connected to the valve with a coupling. The entire unit is attached to a solid base that can be put on a LEGO baseplate (see Figure 1).

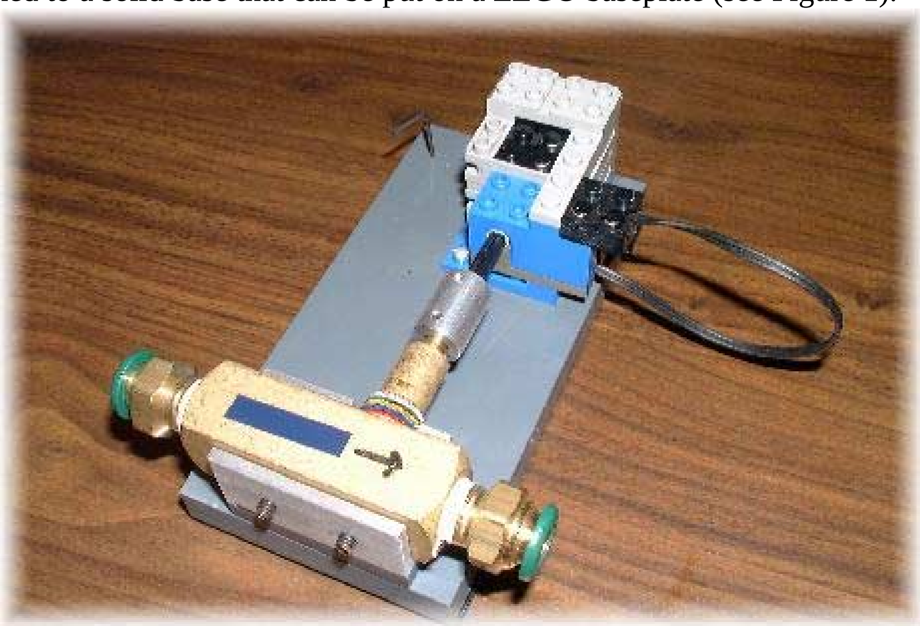
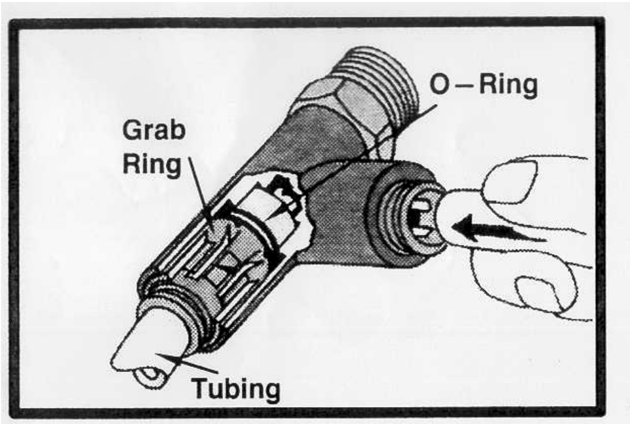


Figure 1. Control valve

Tanks and Piping

The tanks were constructed from polycarbonate tube and plate with diameters of 3 and 4 inches and a height of 8 inches. Two ¼ inch NPT female connections were attached near the bottom of the tank for the pressure gauge and outlet piping. The tubing was 3/8 inch brass tubing with quick-connect fittings. To use these fittings a piece of tubing is pressed into the end and it seals. To release the "pipe", a colored plastic ring is pressed toward the fitting (see Figure 2). Rounding the end of the tubes ("radiusing" the outer edge) allowed them to fit together easily and eliminated leaks. Small submersible pumps (Cole Parmer) were used to circulate the water.



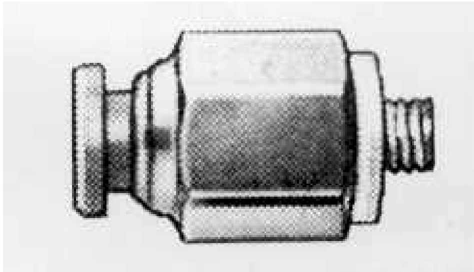


Figure 2: Diagram and picture of quick release fittings (from McMaster-Carr Supply Company Catalogue 99).

Control Algorithm

As mentioned earlier, the LEGO® RCX brick provides the computer interface. Control systems were constructed using ROBOLAB™ investigator software – an adaptation of the National Instrument's LabVIEW™ software developed by Tufts University.[16] The sensor is read and its raw reading is converted to a 0 to 100% range. This signal is sent to a discrete PID velocity algorithm[17], which outputs a change in the valve position. The signal from the controller can be positive or negative depending on which way the motor should go. The programs integrate the both LabVIEW and ROBOLAB languages.

Data Logging Program

This program's function is to collect data from a sensor connected to the RCX and to display that data in real time. Once the data collection is completed, the user may save it to a text file in order for it to be used for analysis. For one exercise, the students performed a step test (sudden increase in control valve position, for example), and the height of the liquid in the tank was recorded by the data logging program. The program also allows for user control of a flow control valve so that, for example, a change in valve position can be logged along with the resulting change in sensor readings. The data could be transferred to ControlStation[18] or a spreadsheet, and a First Order Plus Dead Time model for the system can be obtained.

Another feature of this program is its calibration element. The user may enter a maximum and minimum calibration value to coincide with the raw values of 0 and 1023. (Raw numbers are the values recorded by the RCX when receiving a signal from a sensor). By altering the calibration values, the user can get the computer to output the actual raw values, a range of 0 to 100% of a given attribute, or the actual height of liquid in a vessel.

Control Program

The program collects data from a sensor, enters the value into a PID equation, which outputs a value to represent the necessary valve position change. Like the data logging program, all of this occurs within a while loop which runs until the user presses the stop button. The front panel (see Figure 3) consists of a chart, which displays the calibrated sensor value and another chart, which displays the motor outputs. The front panel also has fields which enable the user to control the setpoint as well as the tuning parameters of the controller.

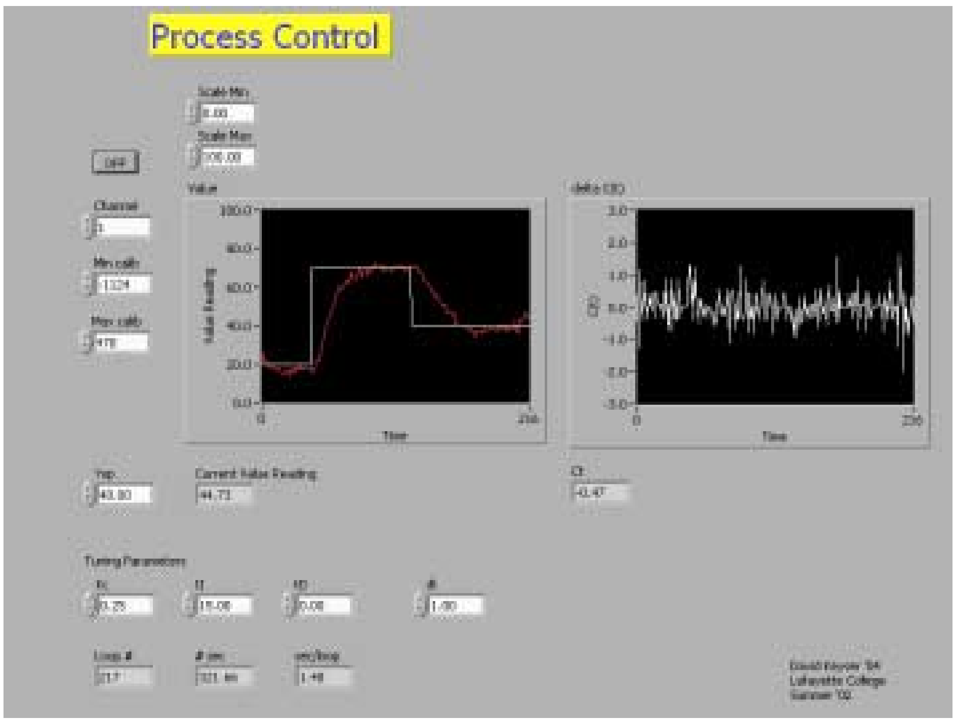


Figure 3. Control Panel for the liquid level control experiment.

The LabVIEW (with RoboLab for LabVIEW extension) wiring diagram for the control program is shown in Figure 4.

Motor Program

The motor program is much different than the other two in that it is completely programmed in RoboLab and is run on the RCX and not the computer. This program serves two functions. It turns the motor when the control program sends it a value, and it initializes the sensor on the RCX. This program must be running before the data logging or control program may run.

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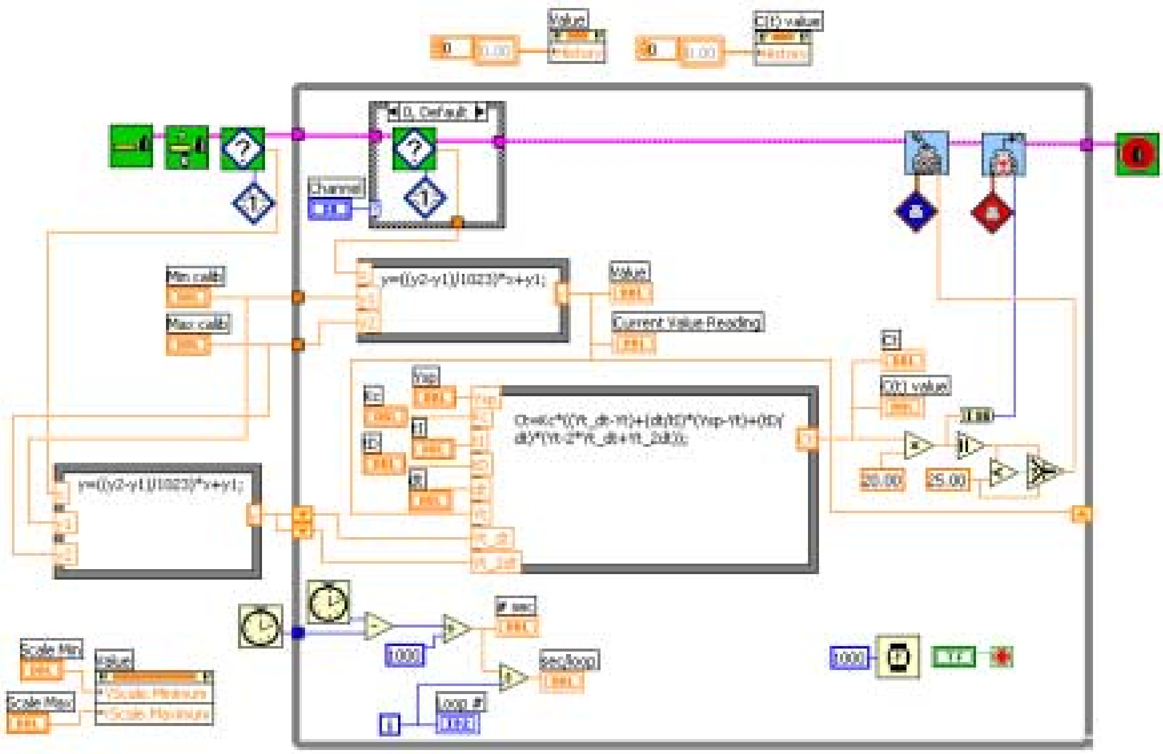

Figure 4: The code diagram for the control program downloaded run on the host computer.

The RCX block has only 5 discrete values of power that it can output, which is not sensitive enough to implement process control. Having the motor respond for a certain amount of time gives a nonlinear response. To solve this problem a pseudo-stepper motor was developed. The motor program has a loop that tells the motor to move a minimum incremental distance for each execution of the loop. The controller sends a signal to the brick that tells how many increments (loops) to take and in what direction. The motor quickly responds, and the students can hear it "click" for each step. Thus, this program turns the LEGO motor into a linear stepper motor.

Each piece of process equipment, sensor, or control valve has quick release fittings. A PC equipped with a LEGO® IR transmitter to communicate with the RCX brick and ROBOLAB™ and LabVIEW™ software is required. LEGO and DUPLO bricks and flat plates in four colors (red, yellow, blue and green) were purchased to build towers and supports. A list of all the parts needed is shown in Table 1.

<u>Safety Considerations</u>

Several precautions are taken to protect the students. A submersible pump is used, which is naturally safe around water. The computer is kept physically separate from the water. Finally, all of the equipment is plugged into a GFCI protected extension cord.

	Description	#	Supplier	Item #	Price/	Total
Electronics						
RCX brick	RCX programmable brick	1	Pitsco-Lego	P979709	122	$122
IR tower	infrared transmitter with serial cable	1	Pitsco-Lego	P779713-013	30	30
3-wire interface		2	Techno-Stuff	3wre	35	70
Lego wire pack	9-volt connecting leads	1	Pitsco-Lego	P970107-108	12	12
pressure sensor	amplified sensor, ±50 mmHg	2	Omega	PX237-050BG4V	125	250
Flow Control Valve						
Lego motor		2	Pitsco-Lego	P775225-013	16	32
Lego rotation sensor		2	Pitsco-Lego	P979891-015	17	34
valve	brass ball needle valve	2	McMaster	5010K72	13	26
coupling	cylindrical coupling with set screws	2				
bracket for valve		2				
Reservoir						
bucket	5 gallon HDPE pail	1	Cole Parmer	06274-25	6	6
submersible pump	max. flow 5.4 gpm, ¼” NPT	1	Cole Parmer	U-07147-40	80	80
Fittings						
brass tubing	brass 3/8" tube, 6 ft length	1	McMaster	8950K58	14	14
flexible tubing	PVC lab tubing 1/4"x3/8"x1/16"	10	McMaster	5231K53	0.2	2
barbed fitting	brass hose nipples female (pk of 10)	1	McMaster	5346K42	7	7
male to quicklock	1/4"NPT to 3/8" brass connectors	8	McMaster	51025K184	2	16
elbow	3/8" elbow	6	McMaster	51025K236	7	42
Lego						
Lego block set		1	Lego	9251	5	5
Lego plate set		1	Lego	9279	5	5
Lego Duplo set		1	Pitsco-Lego	9065	33	33
gray base plate		2	Pitsco-Lego	628	10	20
Holding Tank						
hollow tube	4" polycarbonate tubes, 2 ft length	1	McMaster	8585K22	30	30
plate	1/4" polycarbonate sheet 24"x24"	1	McMaster	8574K55	25	25
					Kit Total =	$861

Table 1: Prototype kit components for two-tank level control system

Results

The LEGO kits were used in the classroom for the first time during the Fall 2002 semester. Twenty-three seniors were enrolled in the course. On the first day of class, a single unit was brought to the class, and simple level control was demonstrated. From the discussion, several process control terms (controlled variable, manipulated variable, set point, disturbance, etc.) were defined. The students observed that control can be “good” or “bad”, depending on some parameters they chose to input into the software. Most of all, the students’ interest was caught by the LEGO tower that held the tank, and the RCX block that interfaced with the computer.

A few weeks later, the class was divided into four groups (red, yellow, green and blue). Each group got LEGO and DUPLO blocks along with the tank, control valve, fittings, pipes a bucket and a pump. Several of the DUPLO bricks had holes drilled through them and worked perfectly as vertical pipe supports . The students were told to construct a system with water being pumped into the tank and exiting by gravity. Each system was different, but by the end of class, each group had a system that worked without leaks (see Figure 5 for a typical unit). An experienced student can assemble the entire system in less than five minutes.

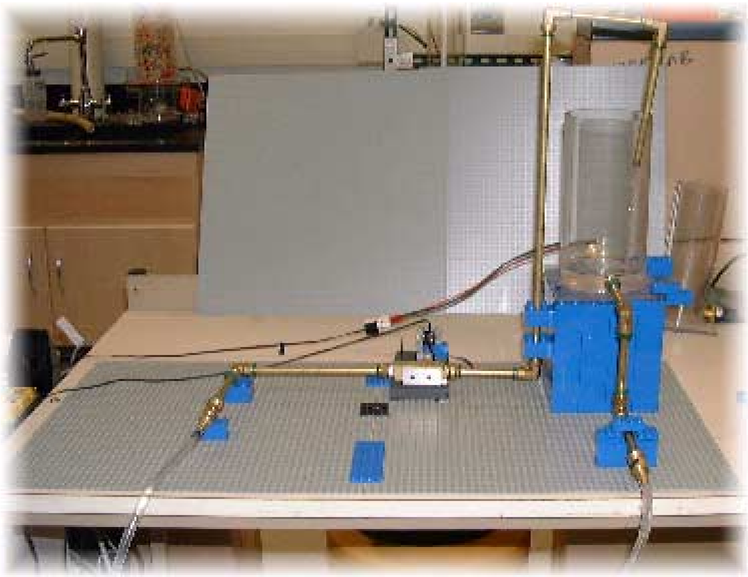

Figure 5. One group's complete unit

In later classes, they were given a handout describing how to install the software and communicate with the RCX block. The students then determined a first order plus dead time model for their tank, after collecting data from a step test of their process. They then were challenged to make step changes in the level set point and observe how the offset changed with the value of gain they input into the controller. They observed how "good" the control was if the control valve was located at various positions in their piping network. They collected data to determine the C_v of the control valve. Finally, they observed how "bad" control parameters can lead to wide oscillations in the control. (They also observed how the pressure head affected the controllability of their system – if the bucket was placed on the floor when they tuned the loop, then was placed on a chair for later experiments, the control was no longer adequate). The student responded positively to the projects: when they saw the LEGO cart in the classroom, they were always excited.

Acknowledgement
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