

AN EFFICIENT PID CONTROL TEACHING MODULE WITH LABVIEW SIMULATION

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Abstract

This paper presents the development and applications of an innovative teaching module for Proportional-Integral-Derivative (PID) control theory. The teaching module consists of a *LabVIEW simulator* and a *PowerPoint presentation*. The module uses a step-by-step approach to teach control concepts, control system performance measures, and PID control tuning. The LabVIEW simulator provides direct visual feedback using the level of a liquid storage tank as the control object; the PowerPoint presentation compares simulation results and explains P, I, and D control components in an intuitive manner. The module allows students to learn by doing, starting with implementing a simple manual control system in LabVIEW, and progressively leads them to P, PI, and PID control schemes. We have used the module to introduce engineering to high school students and teach general engineering students PID controller in a junior-level *Instrumentation and Controls* course. The experiences have demonstrated that this strategic integrated teaching approach can serve as an efficient teaching platform that can be conveniently modified for a range of teaching needs.

Introduction

Despite the emerging of an increasing number of sophisticated control algorithms in the academic research field, PID control dominates 95% applications in industrial process control even in today's highly integrated control systems [1]. Long before it was rigorously treated in mathematics by Minorsky in 1922 [2], concepts of PID control had been used, implicitly or explicitly, in early control devices. Introducing PID control to engineering students

not only teaches them an important control method that is widely used in the real-world, it also brings up an interesting historical review of development and evolution of control theories. Therefore, PID control is a topic usually covered in engineering control courses.

Delivery of PID control with the lecture plus laboratory pedagogical approach [3] has been proven to be effective and has been endorsed by many traditional, disciplined engineering curricula. However, a dilemma surfaces when it comes to teaching this topic in general engineering programs, where courses covering controls topics are fundamental parts of the curricula. According to recent research, all System Engineering (which is often part of general engineering) curricula include at least one controls course [4]. As many disciplined engineering programs see conflicts between the expansion of engineering curricula and practical constraints (e.g., limited credit hours, available instructors, and facility resources), general engineering programs experience much greater challenges in this matter, because they usually have to carry much more compact curricula [5] to cover a broader range of engineering topics.

Virtual laboratories, or simulations based on mathematical models implemented on computers, can be adopted as an alternative to achieve the same learning outcomes as their standard physical counterparts [6-9]. Studies have shown that the new delivery mode provides students with equivalent experiences and no significant differences have been noticed when comparing student learning using physical laboratories versus virtual laboratories [10]. Some research even reported that students who conducted virtual experiments showed deeper levels of cognition in data analysis [11]. It can

be concluded from these references that virtual laboratories can successfully support student learning [12].

A number of virtual laboratories for teaching PID-related topics have been developed, most of which were implemented in MATLAB® [13-16]. MATLAB and its Simulink® toolbox are excellent tools for simulating and presenting results for control topics like system modeling, time and frequency responses, performances of open- and closed-loop control systems, etc. [17-19]. However, it usually requires significant programming time to design a meaningful graphical user interface that can provide students insights into dynamic systems.

This paper presents an innovative module to teach feedback and PID control concepts. The module strategically integrates three approaches to enhance the teaching-learning effectiveness: 1) visualization of control performance with a LabVIEW simulator; 2) intuitive presentation of P, I, and D control components; and 3) students progressive learning by doing. The remainder of this paper is structured as follows: Section II describes a) the development of the first two major components of the module, b) how the two components were integrated in lectures, and c) how students were walked step-by-step through the design of a complete PID control system. Section III reports results from two applications of this teaching module. Section IV summarizes the benefits of the proposed teaching module and discusses pitfalls based on these experiences.

Methods

The two instructional components in the proposed teaching module are a LabVIEW simulator and a PowerPoint presentation. The former primarily include a user interface and three functional units. The latter covers necessary control concepts. The two components, when used in lectures, are integrated to deliver the material.

The Tank-Level Simulator with LabVIEW

The first component of the module is a LabVIEW simulator. The system simulated is a liquid storage tank. The level of the liquid storage was utilized as the control object in the simulator. This was chosen for a number of reasons: a) tank level control systems are frequently seen in bioprocessing and chemical-related industries; engineers in these industries are often required to work on such systems; b) compared to other control objects (e.g., motor speed), fluid levels have reasonably long time constants that allow the students to visually observe the level changes without assistance of any electronic equipment; and c) tank level is intuitive and easier to be visualized than other physical parameters (e.g., velocity or force) and this direct visual effect facilitates the students' natural understanding of transient responses of dynamic systems.

LabVIEW, a graphical software programming environment for data acquisition [20], is utilized to implement the simulator. LabVIEW is widely used for process monitoring and control in industry; it is also popularly used as virtual instruments (VIs) in research/academic environments. LabVIEW provides a wealth of features, including graphical components for user interface design, built-in functions for signal processing, communication/connectivity, data analysis, trend display, data storage, etc. Thanks to its drag-and-drop programming method, one can conveniently implement sophisticated applications in a LabVIEW development environment without having the knowledge of advanced programming codes. The tank level simulation primarily takes advantage of LabVIEW's rich graphical components to construct a tank system with control devices and control performance indicators.

The development of the LabVIEW simulator consisted of four primary tasks (refer to Figures 1 and 2): a) design a straightforward graphical user interface, b) develop a mathematical model of the tank system,

c) implement a digital PID controller, and d) develop the LabVIEW unit for measuring the control performance. Each of these four tasks is explained with greater details in the following subsections.

a. *The User Graphical Interface*

The graphical user interface (LabVIEW front panel) of the simulator shown in Figure 1 consists of three elements. These include:

1) *A tank system* (on the upper half of the interface): This system includes a tank with a level gauge and a required input/output piping system (an input pump, an input valve, and an output valve). To mimic the real operation of a fluid system, the pump and valves are set to work in an ON/OFF mode which will allow or stop flow of the fluid in the piping system.

2) *A control panel* (on the right-hand-side): This panel allows the user to adjust system settings and control coefficients. Adjustable parameters include P, I, D coefficients, tank-level set point, and tolerable error band (usually 5% or 2%).

3) *A control performance display unit* (on the bottom left of the interface): This unit shows the continuous change of the tank level compared with the level set point in the same plot. It can also numerically report the control performance measures of the system: *rising time* (t_r , in minutes), *settling time* (t_s , in minutes), *percentage overshoot* (P.O, %), and *steady-state error* (SSE, %). The level change and performance measures are all updated in a real-time manner.

b. *The Mathematical Model of a Tank System*

In the simulator, a cylindrical tank with a diameter of 3 feet and a height of 10 feet was used as the control object. At any time t , the fluid level $H(t)$ in the tank is given by:

$$H = \int_{t_0}^t \frac{Q_i - Q_o}{A} dt \tag{1}$$

where Q_i is the input flow rate; Q_o is the output flow rate; t_0 is starting time; and A is the cross sectional area of the tank (28.3 ft²).

In the simulator, the tank level H is obtained through a numerical integration using Euler’s method over time, where the step-length Δt depends on the simulator’s sampling rate.

$$H(n) = H(n - 1) + \frac{Q_i - Q_o}{A} \Delta t \tag{2}$$

where: $H(n)$ is the tank level of the current sample cycle; and $H(n - 1)$ is the level of the previous sample cycle.

In a controlled tank system, the designed controller determines the input flow rate $Q_i(n)$. The output flow rate $Q_o(n)$, derived by applying the steady state fluid energy equation to the system, is:

$$Q_o(n) = A_d \sqrt{\frac{2gH(n)}{1+K}} \tag{3}$$

where: $H(n)$ is the tank level; K is the loss coefficient for the exiting pipe system; A_d is the cross sectional area of the drain tap of the tank; and g is the gravitational acceleration constant (32.2 ft/s²).

To simplify the development work, the tank system was modeled with a few approximations without sacrificing the conveying of concepts. We assumed that input flow has an unlimited supply; i.e., the desired input flow rate—determined by the output of the PID controller—can reach any value obtained from the control algorithm. It is also assumed that an overflow mechanism exists so that when the mathematically calculated tank level exceeds the maximum tank capacity, the tank level is forced to equal the maximum tank height (10 feet in our model). Also, we did not fully

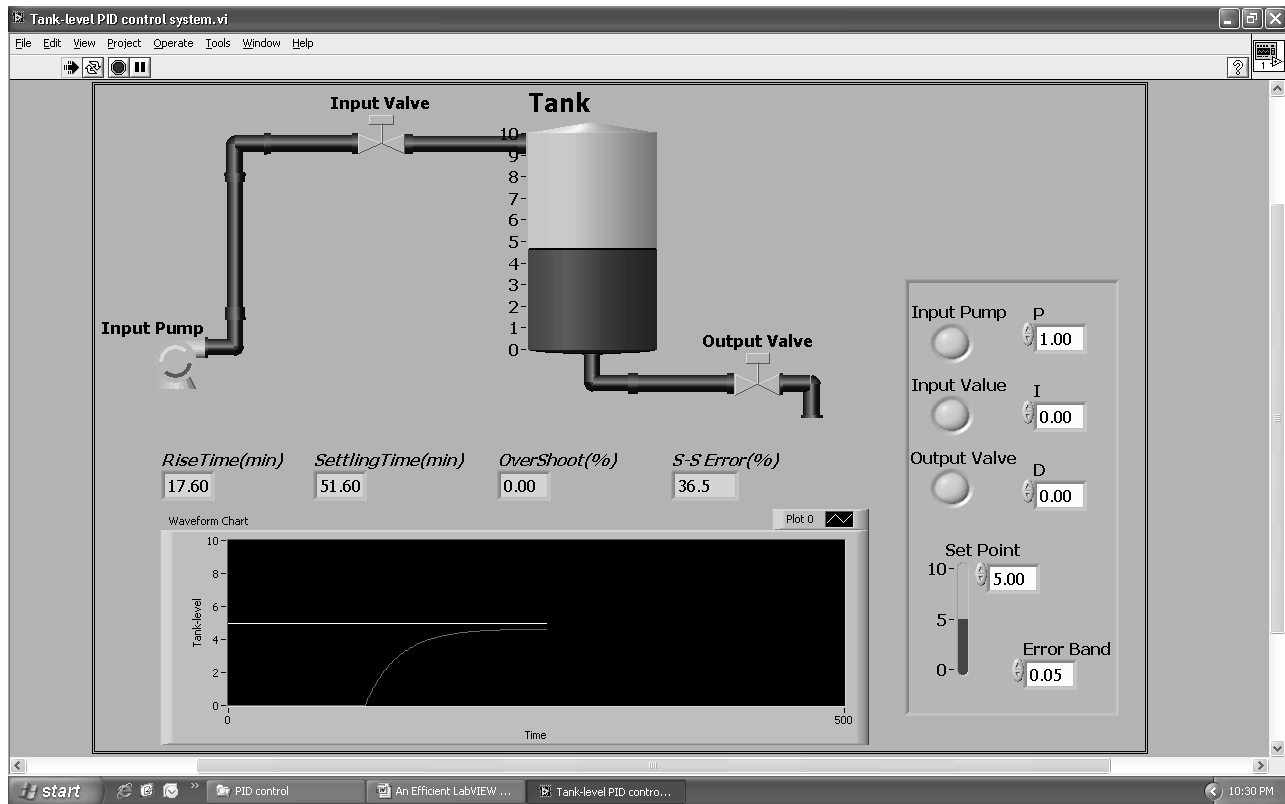


Figure 1. The LabVIEW User Interface of the Tank-Level Control Simulator.

define the exiting piping system of the tank; instead, we simply chose a constant value for K .

c. The Digital PID Controller

A PID control algorithm is usually presented as an integral-differential equation [21]:

$$Q = K_p e(t) + K_i \int e(t) dt + K_d \frac{de}{dt} \quad (4)$$

where: Q is the controller's output which is the input flow rate; $e(t)$ is the deviation between the actual tank level and the set point; K_p , K_i , and K_d are the proportional, integral, and derivative coefficients, respectively.

The digital PID controller implemented in the LabVIEW diagram takes the form of a difference equation:

$$Q(n) = Q(n-1) + k_1 e(n) + k_2 e(n-1) + k_3 e(n-2) \quad (5)$$

where: $Q(n)$ is the flow rate to be determined by the controller; $Q(n-1)$ is the flow rate of the previous sample cycle; $e(n)$ is the tank level deviation from the current cycle; $e(n-1)$ is the tank level deviation from the previous sample cycle; $e(n-2)$ is the tank level deviation from the cycle before the previous; and k_1 , k_2 , and k_3 are control constants derived from coefficients K_p , K_i , and K_d using the following relationships:

$$k_1 = K_p + K_i + K_d \quad (6)$$

$$k_2 = -K_p - 2K_d \quad (7)$$

$$k_3 = K_d \quad (8)$$

d. Control Performance Measurement

The performance of the control system is evaluated with four measures: *rising time* (t_r),

settling time (t_s), and *percentage overshoot*

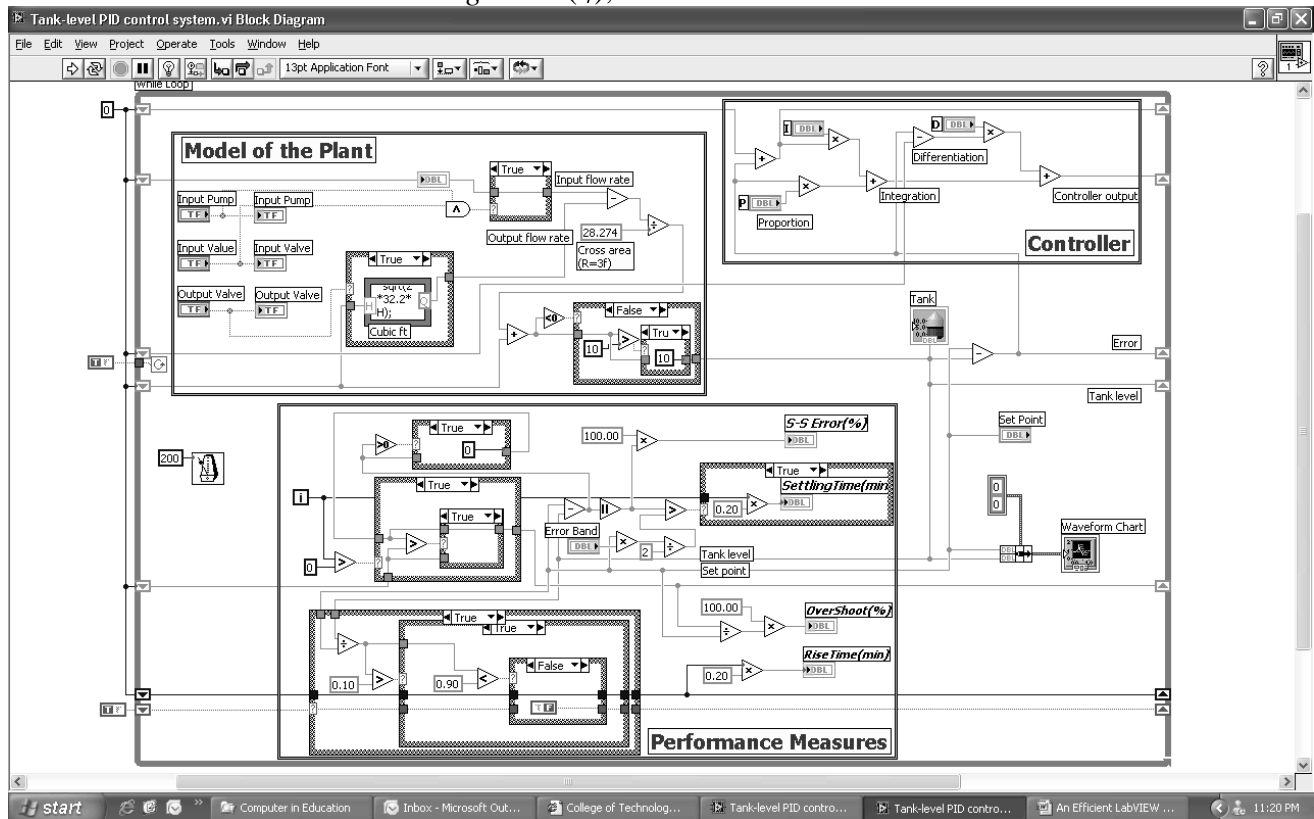


Figure 2. The LabVIEW diagram of the simulator consisting three major units: the tank model, the controller, and the performance evaluating unit.

(*P.O.*) are used to measure the system transient response and *steady state error* (*SSE*) is used to measure the system steady response. The LabVIEW diagram (shown in Figure 2) was designed in a way that all these four performance measures can be calculated in real time. This information is then immediately updated in the user interface in Figure 1.

The PowerPoint Presentation

The second important component of the teaching module is the *PowerPoint presentation*. To make it a stand-alone delivery module, topics introduced in the module include: basic feedback control concepts, PID control modes, PID parameter tuning, and general design strategy. All these items are presented concisely without

overwhelming mathematical derivation. The introduction is outlined with brief descriptions of each topic in the following paragraphs.

a. Feedback Control Basics

The basics for feedback control include a simple block diagram and the control performance measures using a system's step response. A simple block diagram (see Figure 3) helps the students understand a set of feedback control concepts and the relationships among them: control plant, set point, actual output, error (deviation), control law. These concepts are given in the context of a practical application such as room temperature (air conditioning) or automobile speed control.

Control performance measures, as described previously, are then introduced with a plot for

the step response of a typical second-order system (see Figure 4). The four performance measures follow the definitions in [21].

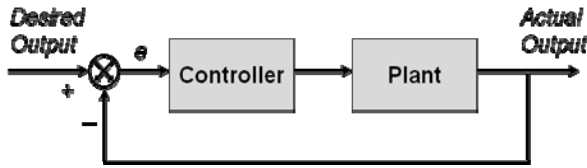


Figure 3. Block diagram of a control system.

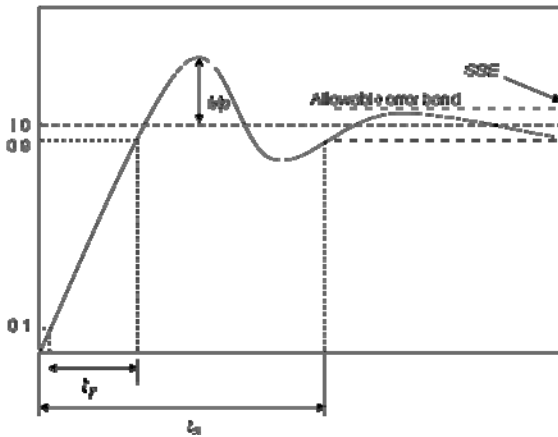


Figure 4. Performance measures with a typical step response.

b. PID Control

The meaning of the term “PID” is first explained to help students make connections between controls and mathematics. The history [2] and broad applications of this classical control law [1] are reviewed. After that, the mathematical implications of each component are further detailed as contributions of the three basic control components: Proportional, Integral, and Derivative. Each is explained in terms of the deviation of the actual output from the set point, as shown:

$$Q_p = K_p e(t) \tag{9}$$

$$Q_i = K_I \int_0^t e(\tau) d\tau \tag{10}$$

$$Q_d = K_D \frac{de}{dt} \tag{11}$$

To better explain each of these control components, a couple of techniques are used: a) bring in a control component with a practical application that requires this component’s contribution to the performance, and b) intuitively explain each control component’s effect on the controller’s output. Table I summarizes the applications used to introduce each component and the intuitive explanation of the component’s effect on the system performance. As an example, missile control is used to start the discussion of integral control. In this application, the missile has to hit the target; existence of any steady-state-error will cause the missile to fail this goal. Integral control is therefore introduced to eliminate the steady-state-error and meet the application needs. Please note that the examples are for intuitive “illustration” purpose and description may not be completely strict.

After studying all the three control components, and explaining how they are applied in different situations, PID parameter tuning is summed up with general guidelines (Table I): make tradeoffs between all the performance measures and make the system as simple as possible.

Table I.
TECHNIQUES USED FOR CONTROL COMPONENT EXPLANATION

Application	Requirements	Intuitive effect
P Room temperature control	Usually no special requirement. Cost is the top concern, which requires the system to be simple.	The output of the controller is proportional to the deviation
I Missile control	The goal of the missile is to hit the target; i.e., no steady-state-error is allowed	Integral control adds a “memorization” effect to the output of the controller and eliminates steady-state-error
D Automobile speed	For passenger’s comfortableness, speed fluctuation is not acceptable. i.e., overshoot should be avoided.	Derivative control adds a “prediction” of the future change of the deviation and therefore stabilizes the system.

Integration of the Simulation and Presentation

When delivering the control modes, PowerPoint slide lecturing is integrated with LabVIEW simulation as illustrated by the flowchart in Figure 5. In PowerPoint slides, each mode is first brought in with an application need as described earlier; LabVIEW simulation is conducted to demonstrate how each control mode meets the needs. The simulation results are then recorded in a table (See Table III) so that all the performance measures for the three modes can be compared side-by-side to help students see the contributions of different control components (i.e., P, I, and D).

When running the simulation, the control performance display chart on the graphical user interface in Figure 1 helps to compare the performance of the system with different combinations of control coefficients, because the chart can display multiple simulation results in the same window. Figure 6 shows simulation results from three sets of control coefficients, where all the cases have $K_p = 10$, $K_I = 10$, and the derivative coefficient $K_D = 0, 1, \text{ and } 5$,

respectively for the three cases. The corresponding overshoots are 53.2%, 46.7%, 40.8%. This figure visually compares the overshoots and enhances students’ cognition and understanding of the fact that a strong derivative component of a PID controller typically decreases the system overshoot.

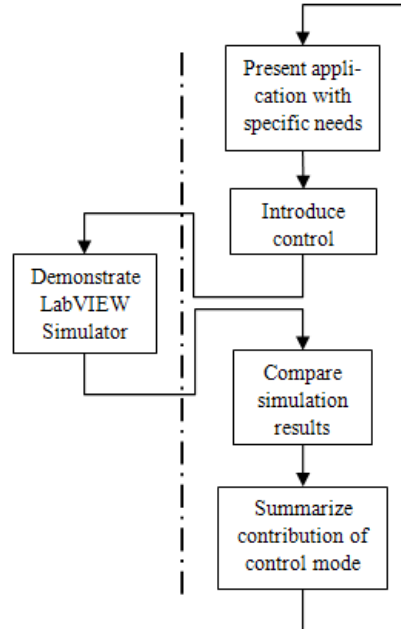


Figure 5. Integration of simulation with PowerPoint Lecturing.

TABLE III.

COMPARISON OF PERFORMANCE MEASURES WITH DIFFERENT CONTROL COEFFICIENT COMBINATIONS

	P			PI			PID		
k_p	5	10	20	10	10	10	10	10	10
k_i	0	0	0	0.5	0.75	1	0.75	0.75	0.75
k_d	0	0	0	0	0	0	2	5	15
t_r (min)	2.6	1	0.2	0.8	0.6	0.4	0.6	0.8	0.8
t_s (min)	Inf.	2	0.6	7	7.8	8.2	6	5.8	5.4
M_p (%)	0	0	0	8.3	12	15	11	11	10
SSE (ft)	3.2	1.6	0.8	0	0	0	0	0	0

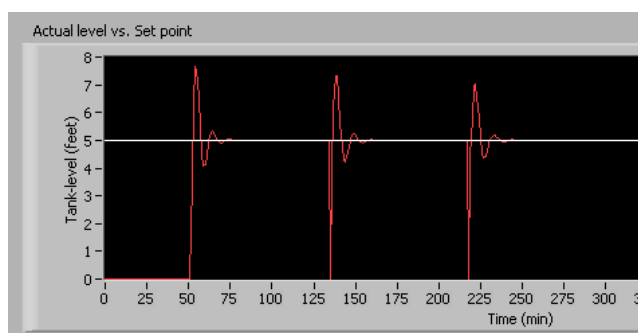


Figure 6. Comparison of overshoots from PID controllers with different derivative components.

Progressive Learn by Doing

Since programming with LabVIEW is straightforward, one additional teaching technique that can be used with the module is to have the students implement the controllers with LabVIEW after presenting the three PID components. The students may start with a simple manually controlled tank-level system (see Figure 7) to acquire the needed LabVIEW skills. This also increases their understanding of the dynamic characteristic of a tank system. Then the students move into more advanced P, PI, and PID controllers progressively. After this learn by doing experience, the students gain good understanding of the combinations of the control modes.

Results

To date, we have used this PID education module for two different purposes: one was to teach high school students; the other to teach seniors in a general engineering program. In both cases, the delivery was received well and students were able to understand most of the PID concepts within a very limited time.

High School Outreach

In 2006 summer, we applied this module to North Carolina Summer Ventures in Mathematics and Science to expose high school students with engineering and the application of mathematics in engineering. During the first three weeks of this four-week program, PID control, along with 3D solid modeling and programming logic controllers, was used to introduce typical engineering topics. PID control with the proposed teaching module aimed to helping talented high school students understand applications of mathematics in the real world. The interleaving approach introduced earlier was first used to give the students the necessary feedback control background and present PID control modes. The students, after stepping through a simple manually-controlled tank level system, implemented a P, PI, and PID controller consecutively.

During the available time, all the 17 students were able to program LabVIEW VIs to complete all three functional controllers. One of the students was very interested in the mathematics behind PID and decided to explore more during the last week's independent research. After closely examining the provided LabVIEW program, he successfully converted the LabVIEW version of the PID controller into an Excel spreadsheet with macros. In the reflection session at the end of the program, some other students expressed their excitement about the fact that they had been able to learn and understand PID control at an advanced level, something they had never expected.

A survey conducted at the end of the program demonstrated that 88% of the students agreed that they have learned from this module. However, because this was the first time the module was used, close to half of the students expressed that they would benefit more if more LabVIEW instructions had been given. In addition, one student mentioned that the mathematics was difficult. We should note that these students are competitively selected and much more advanced than typical high school students.

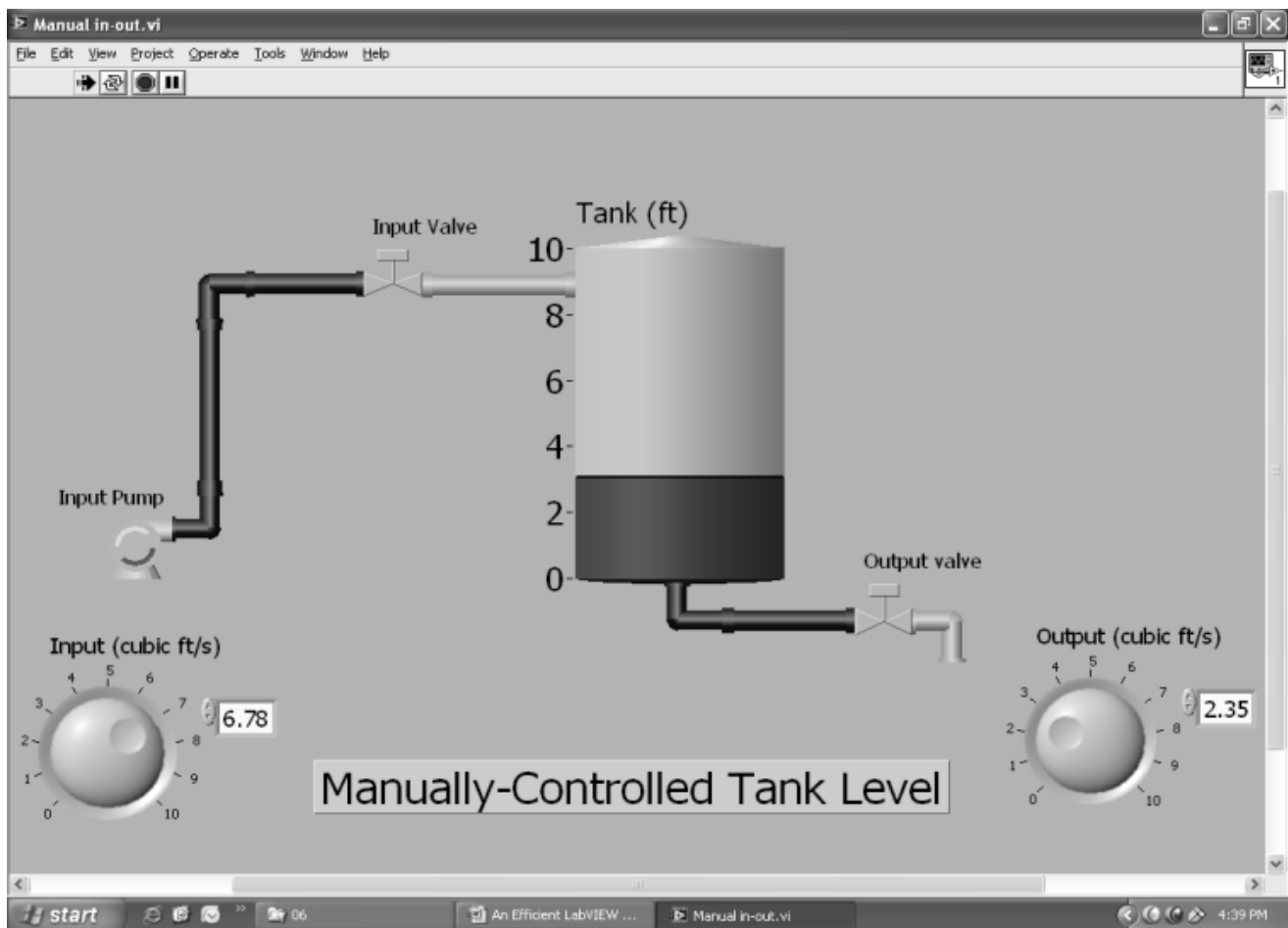


Figure 7. A manually control tank-level control system.

Teaching an Instrumentation and Control Course

In Fall 2007, this module was used in an *Instrumentation and Controls* course (senior undergraduate course) in a general engineering curriculum at East Carolina University [22]. As its name suggests, this course aims to providing students with basic concepts on the two topic areas: *instrumentation* and *controls*. The PID control teaching module was used after the introduction of all the basic feedback control concepts (transform functions, system performance, and stability, etc). A fifty-minute lecture was used to teach PID with this module. Because the students all had the necessary calculus background, the visualization of the tank system and intuitive explanation of each component made the abstract mathematical material easier and deepened their understanding of integrals and differentiations. The students got an average of 94% for a question on PID control in the final exam, demonstrating that the students received the material well in spite of the limited time spent on the topic.

Discussion

The two examples demonstrated different application possibilities of the module: the Summer Ventures activity allowed high school students to see how mathematics are applied to real-world problems and made calculus accessible to those have no prior knowledge; the use of the module in the *Instrumentation and Control* course, on the other hand, visualized the control concepts that had been derived in mathematics and provided substantial insights of the control schemes originally presented in differential equations. Results from the two applications showed preliminary success of using the proposed module to deliver PID controls. Compared to physical experiments, the simulation requires no cost on equipment and much less time to complete. In addition to the efficient coverage of PID control, the learn-by-doing approach utilized with the module adds a side benefit: it exposes the students with

LabVIEW, a popular software package that engineering graduates are very likely to see in their future.

There are several opportunities to extend the applications of this teaching module. For example, the module can be used along with Ziegler-Nichols method to provide a systematic way to tune P, I, D coefficients and give students more insights in the control algorithms. Furthermore, because the module does not require physical equipment, it can be conveniently migrated from face-to-face instruction to distance education. The web-based laboratory model allows the students to interactively change the control coefficients and control modes, observe dynamic changes, and compare simulation results. This interactive and repeatable virtual laboratory provides students with more flexibility and should promote student-centric learning.

Conclusions

This paper presented a PID control teaching module. The strategically integrated module combines visualization, intuitive explanation, and learn-by-doing pedagogical methods and provides a time/cost efficient solution to teach feedback control and PID control related topics. Two application experiences have shown that the module can actively engage students and enhance students learning. Further integration of other PID coefficient tuning approaches and web-based extension can make the module better serve other teaching environments.

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