Small-scale low-cost process control trainers

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Abstract

Preparing students for jobs in the process control and instrumentation industry by teaching practical instrumentation and control courses can be difficult if not impossible without appropriate lab equipment. Traditional solutions involve purchasing and installing Interactive Plant Environment (IPE) systems or more compact process control trainers (PCT). Both are hugely expensive and often require labs to be performed in large groups as opposed to more individualized instruction. Therefore, alternative inexpensive lab equipment for teaching process control and instrumentation courses is often necessary. This paper presents several small-scale, inexpensive, and modular process control trainers suitable for teaching specific learning objectives. The goal of this paper is to give readers new and/or improved ideas for designing, building and utilizing various lab equipment to optimize the teaching of instrumentation and control classes and labs.

Keywords

Process, control, PID, instrumentation, trainer.

1. Introduction, problem description and objectives of this paper

1.1 The importance of training students in process control and instrumentation

As graduates are being prepared for the jobs of today and tomorrow (the main topic of the 2023 ASEE Midwest Section Conference), one industry seems to garner less attention than it deserves: the process control and instrumentation industry.

Process control and instrumentation is a field of engineering that deals with the monitoring and control of machines, systems and processes across various industries. It involves the use of sensors, actuators, controllers, software and hardware to measure and manipulate physical variables such as temperature, humidity, pressure, flow, level, pH, force, speed, etc. Process control and instrumentation aims to improve the efficiency, quality, safety and reliability of various industrial operations [1].

Some of the major industries that use process control and instrumentation are power generation, refineries, petrochemicals, chemical manufacturing, bio-technology, food processing, water and wastewater treatment, etc. [2] For example, in a nuclear power plant, the temperature and flow of cooling water is precisely controlled to keep the process in a safe and efficient operating region. In the chemical industry, process control ensures that chemical agents are combined in a specific order, an exact ratio, a prescribed temperature, and at a specific pressure to produce a product that conforms to desired specifications [3].

1.2 Theory vs practice

While trying to prepare students to work in the process control and instrumentation industry, the majority of university process control courses unfortunately only concentrate on theoretical concepts such as Laplace transforms, root locus analyses, Routh & Nyquist stability criterion, etc., which are suitable for linear continuous systems with known and well-defined transfer functions. However, practical aspects of industrial importance such as design and operation of various instrumentation devices and actuators, programming and tuning of real-world controllers, non-linear processes, PLC systems, distributed control systems (DCSs), national standards and regulations, etc., are often omitted altogether [4].

1.3 Interactive Plant Environments

To bridge the gap between theory and practice, to provide students hands-on training with actual process control equipment, some engineering schools invest large monetary and space resources in Interactive Plant Environments (IPE).

Figure 1: Interactive Plant Environment by Emerson [5]

IPEs are facilities that simulate real industrial plants with various process control systems and instrumentation devices. They allow students to learn and practice various skills in a safe and controlled environment, using real devices, software and data. They also enable instructors to create realistic scenarios and problems for students to solve, such as commissioning, calibration, troubleshooting, optimization and safety [5], [6].

1.4 Commercially available process control trainers

Most engineering schools do not have the space and money to provide IPE for students, so the next best option is to use Process Control Trainers (PCT). PCT are really IPE in a miniature format, often small enough to fit on a single workbench or cart, with small tanks, pipes, pump, motors, etc., but with real sensors, actuators and controllers to simulate a real-world system. Examples include [7]-[14].

Figure 2: Process control trainer from Amatrol [7]

1.5 Lab equipment at K-State Salina

While more affordable than IPE, PCT are still a substantial investment. At K-State Salina, two process control trainers from DeLorenzo were purchased. They were significantly cheaper than their competition, but still cost about $20k each (2021 prices).

Figure 3: Process control trainer DL 2314 from DeLorenzo [15]

Ideally, more process trainers would have been needed, maybe eight for 24 students, but the budget would not allow for it. Therefore, labs were often run in large groups, with limited time for each group, and even less time for each student.

In addition, once operational, it was discovered that these process control trainers had several shortcomings: the water heater was grossly underpowered, and took the whole lab period (close to 2 hours) to heat up the water in the process tank. The pump cavitated when trying to limit the flow via a valve, so flow control was not possible. And the process tank was not airtight enough to allow pressure control experiments. So instead of the advertised 4-process trainer, this trainer could only be effectively used for teaching one single process (level control).

Level and temperature control processes have a very slow response time, are easily controllable by basic On/Off control schemes, and are not well suited for demonstrating the advantages of linear (i.e. PID) control techniques. In addition, all sensors and actuators of the trainers were essentially black boxes with already built-in signal conditioning (operating on 0-10 V signals), so the students missed out on other essential instrumentation learning objectives such as sensor types, signal conversion techniques, amplification, filtering, etc.

1.6 Objectives and layout of this paper

Therefore, the authors set out to design and build alternative improved, small-scale, modular, inexpensive lab equipment to help teaching various instrumentation and process control concepts. The objective of this paper is to give readers new or additional ideas about how to design, build, and utilize inexpensive lab equipment when teaching process control and instrumentation courses and labs. To this end, several already published projects will be discussed in section 2, then several of the authors' projects will be described in section 3. Discussions, suggestions for future work, and conclusions will be presented in section 4.

2. Published work (i.e. literature survey)

There are several publications that deal with the subject of low-cost process control teaching lab equipment. Below is a summary of some similar work that has been done in the last 5 years.

2.1 Electro-mechanical equipment

A quite popular method to help teach PID control courses involves using various electromechanical contraptions whose speed and/or position is controlled by DC motors, e.g. [16] and [17]. In the latter, the position of an arm is controlled by a DC motor, and OpAmps, LabView and MATLAB/Simulink were used to control the motor via various control algorithms.

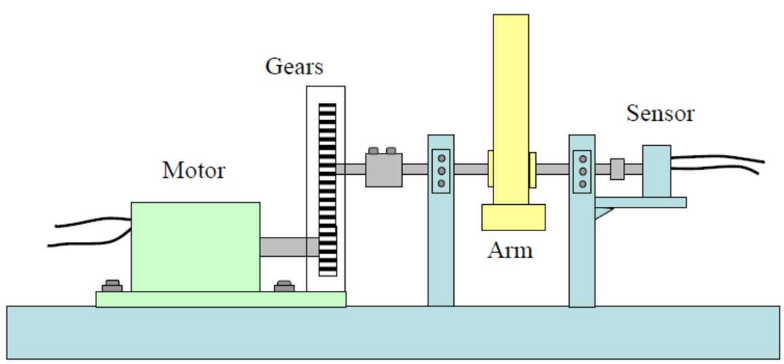

Figure 4: DC motor control trainer [17]

Another popular method to teach various control algorithms is by using an inverted pendulum to try balance it in the upright position. Different platforms and controllers have been used, some commercially built, some custom made with varying degrees of sophistication (e.g. [18]-[21]).

Figure 5: Self-built balancing robot [20]

A variation of the same theme is using a so-called aero-pendulum, in which a motor, coupled with a propeller, attempts to hold an arm in an upright position (e.g. [22], [23]).

Another common tool to teach PID control is the floating-ball device. A variable-speed fan blows air into a tube, causing a ping-pong ball to float. Again, there are several examples with varying degrees of sophistication (e.g. [24] - [27]).

2.2 Other process control equipment

There appear to be only a few publications that deal with trainers for common processes such as level, flow, pressure and temperature. There are some publications that develop specialized lab modules to teach fluid power classes (e.g. [28], [29]). There is also a basic temperature On/Off project utilizing a thermistor and a fan to keep the temperature in a room or compartment between an upper and a lower limit [30]. Then there is an Arduino based temperature shield utilizing transistors as heaters, and thermistors to sense their temperature [31]. There is also a multivariable control system that mixes hot and cold water to obtain the desired level and the desired temperature in a tank [32]. Another publication presents multiple process-control lab equipment pieces to help teach various EET classes [33].

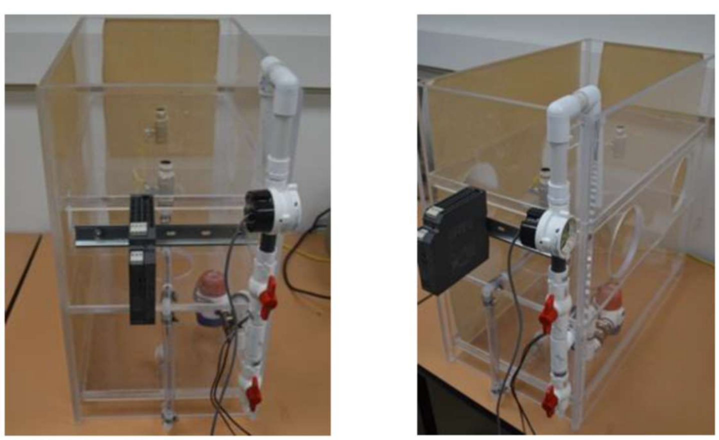

Figure 6: Self-built level control trainer [33]

3. Low-cost process control trainers at K-State Salina

Based on the needs as discussed in section 1, and expanding on some ideas presented in section 2, the following process control training systems were designed and built.

3.1 Low-power temperature control trainer (ThermalCAT)

3.1.1 Construction

A low-power temperature control system (named "ThermalCAT") was adapted from an MIT project poster presented at National Instruments NI Week conference in 2018 [34]. Also somewhat similar to [31], the system relies on basic concepts of heat dissipation by a BJT transistor as current passes through it. A thermistor was attached to the transistor using thermal conductive compound and heat-shrink tubing to measure the temperature of the transistor.

Figure 9: ThermalCAT trainer PCB board

The uniqueness of this trainer is that the circuit board and several LEDs were packaged into a scaled-down accurate model of nuclear power plant cooling tower [35] which was printed on a 3-D printer. The cooling tower makes the heating process seem more realistic. Instead of controlling the temperature of a transistor, students could visualize controlling a much bigger real-world thermal system by utilizing the same principles as applicable to a much smaller and simpler system.

Although an actual cooling tower relies on natural convection, our design adds forced convection driven by a small fan at the top of the tower. It is an additional process parameter that changes the operation of the system, and adds more flexibility to a lab module.

The total cost of the trainer was <$100, and several more are being planned for the future.

Figure 10: ThermalCAT trainer construction

3.1.2 Operation

The ThermalCAT needs a 24 VDC power source to run the LEDs, heat the transistor, and operate the cooling fan. The control signal, which needs to come from an external controller, is 0-5 V so the system can be directly controlled by OpAmps, microcontrollers (e.g. Arduino), or with higher-level software packages such as LabView, MATLAB, SIMULINK, etc., (with appropriate IO devices), or with a Programmable Logic Controller (PLC) with analog IO.

A variety of lab exercises can be done with this trainer, e.g.

- Temperature sensors - thermistors
- On/Off control
  - With comparators
  - With microcontrollers (e.g. Arduino)
  - With LabView / MATLAB / SIMULINK
  - With PLC
- PID control
  - With OpAmps
  - With microcontrollers (e.g. Arduino)
  - With LabView / MATLAB / SIMULINK
  - With PLC

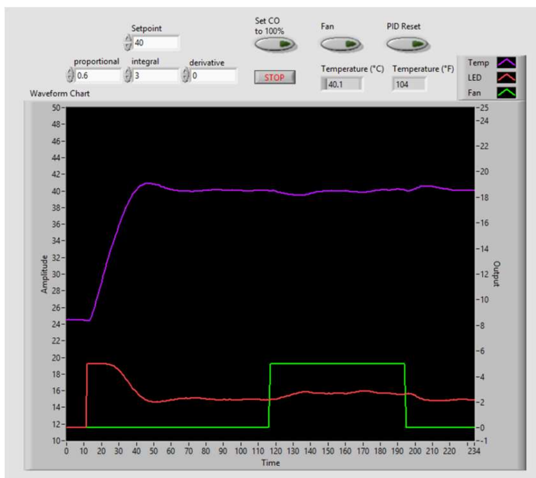

Figure 11: ThermalCAT in action (controlled by LabView)

3.2 High-power temperature control trainer

3.2.1 Construction

As mentioned in section 1, the DeLorenzo heater is grossly underpowered and could not provide sufficient watts to heat up the water in the allotted time frame. Therefore, this project started with the idea that a much more powerful (i.e. higher watt) heater was necessary for running practical temperature-control experiments.

A very common and inexpensive water heater was found in the form of an electric kettle available in many stores including Wal-Mart [36]. Designed to heat water for tea, it typically has a powerful 1500 W @120 VAC rating, and is able to bring 1.5 L of water from room temperature to boiling in less than 5 minutes.

The kettle has an On/Off switch, but to make the heating process more controllable, a modulating power controller from Watlow [37] was used. It can vary the power output of the heater from 0 to 100% in response to a 4-20 mA control signal.

The 4-20 mA control signal can be obtained from multiple sources, but in this case, a dedicated temperature controller made by Delta [38] was used. The temperature controller can be directly connected to various temperature sensors such as thermocouples and RTD. Based on the sensor input, a programmable setpoint, and the desired control scheme, the controller then sends out a 4-20 mA signal to the modulating power controller to precisely vary the output of the heater.

To make the trainer even more versatile, instead of connecting a temperature sensor directly to the temperature controller, a dual-input temperature transmitter from Omega was used [39]. The transmitter can be programmed to receive different types of input signals and converts them into a 4-20mA output. Having the transmitter allowed us to utilize two different industrial grade temperature sensors: a J-type thermocouple from FactoryMation [40], and an RTD sensor from AutomationDirect [41].

The whole system cost us about $500; about half of the cost is due to the indispensable power modulator. Some components (e.g. the transmitter and the temperature controller) can be omitted if other 4-20 mA sources are available, and less expensive sensors could also be used to save cost if necessary.

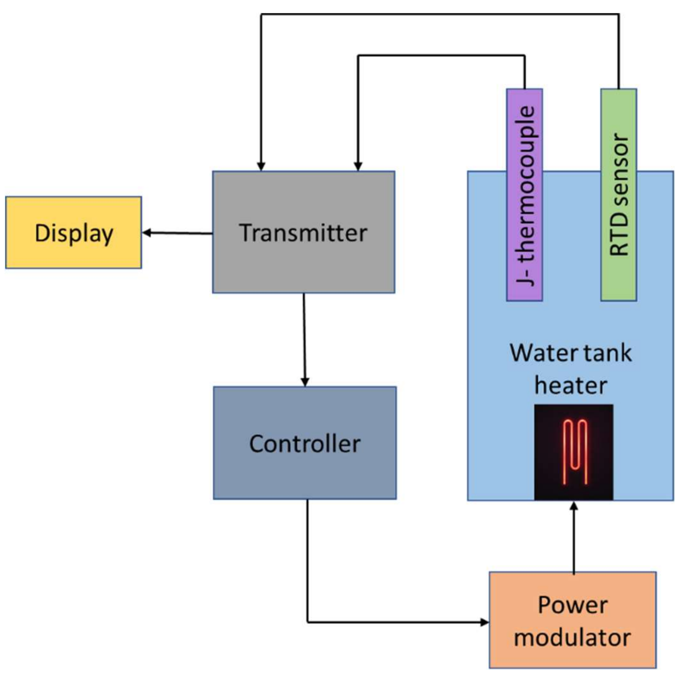

Figure 12: Block diagram of the high-power temperature trainer

3.2.2 Operation

As described above, the high-power temperature trainer is designed to operate as a fully independent, stand-alone system, powered by 120 VAC. The primary teaching lesson when using this trainer might be how to configure and program industrial grade instrumentation and control equipment.

However, because it is modular, it can also be used to teach various other topics. For example, by bypassing the transmitter, it can be used to teach how to convert RTD or thermocouple signals into 4-20 mA control signals via OpAmp amplifiers. Or by bypassing the industrial temperature controller, it can be used to teach how to control the temperature process with PLC, LabView, or Arduino microcontrollers.

As with the low-power temperature process trainer, various lab exercises can be run with it, e.g.

- Temperature sensors – thermocouples
- Temperature sensors - RTD
- Signal conditioning
- On/Off control
    - With the industrial temperature controller
    - With comparators
    - With microcontrollers (e.g. Arduino)
    - With LabView / MATLAB / SIMULINK
    - With PLC
- PID control
    - With the industrial temperature controller
    - With OpAmps
    - With microcontrollers (e.g. Arduino)
    - With LabView / MATLAB / SIMULINK
    - With PLC

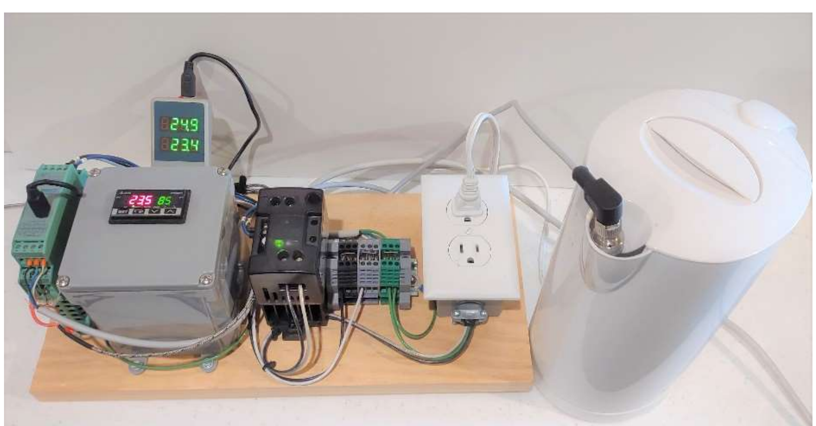

Figure 13: High-power temperature trainer in action

3.3 Inverted pendulum trainer (StableCAT)

3.3.1 Construction

As discussed in section 1, level and thermal processes are not well suited for demonstrating the advantages of linear (e.g. PID) control techniques. Therefore, an inverted pendulum trainer and a floating-ball trainer to teach PID concepts were designed and built.

There are several examples mentioned in section 2 already, but the primary idea for this inverted pendulum trainer (named StableCAT) came from [42]. The design uses an Arduino Pro Mini microcontroller board as the "brains" of the system. The Arduino board receives input from a six-degrees-of-freedom Inertial Measurement Unit (IMU) and calculates the trainer's standing angle. The IMU board contains an MPU-6050 Microelectromechanical Systems (MEMS) device with built-in 3-axis gyroscope, 3-axis accelerometer, and Digital Motion Processor (DMP).

The mechanical design of StableCAT is similar to the design on the YABR site [42]. The main body was modeled by a 3D software to check the fit of each part. The Mechanical Lab on the K-State Salina campus has a CNC laser cutter capable of cutting thin plywood and acrylic. The 3D design was then transferred to flat patterns, which could be read by the laser cutter software. Parts for the main body were cut from 3mm plywood, and a clear acrylic back panel was made to allow viewing of the electronic components. The 3D printed wheels are powered by stepper motors controlled by a DRV8824 driver.

The StableCAT has the option of moving around using a remote controller. The remote is constructed from a standard Wii Nunchuk from a Wii gaming console. The signals from the Nunchuk joystick are routed to an Arduino board and then a transceiver inside the Nunchuk provides a wireless link to the StableCAT.

The total cost of the system is <$100 including batteries, and several of them are already built and in operation on the K-State Salina campus.

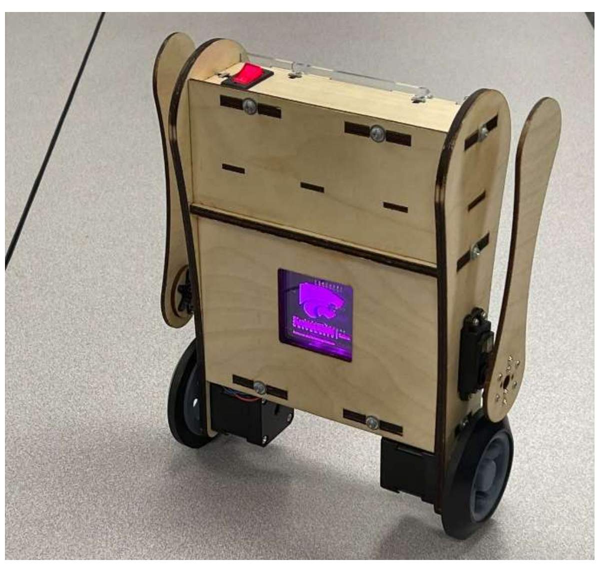

Figure 14: StableCAT in operation

3.3.2 Operation

To remain upright, the Arduino board computes the difference between the actual angle of the trainer and the desired upright position. The difference is the process error. Using a PID algorithm, the microcontroller then moves the motors in the appropriate directions to maintain the vertical position angle with minimal error.

Once the StableCAT is positioned upright, it can be moved around like a typical remote-controlled car using the Nunchuk controller. Depending on the tuning of the PID controller it might work well or not so well (i.e. it might fall down or oscillate in the upright position). Therefore, the primary teaching lesson with this trainer might be how to design and operate different PID control algorithms, and how to determine appropriate tuning parameters to improve the performance of the system.

System stability performance can be viewed via the Arduino IDE, LabView dashboard, etc., and conclusions about the performance of the algorithm can be drawn based on the oscillations seen on the chart. PID gains can then be adjusted by sending new values from the dashboard to the StableCAT. The effect of the new gains will be visible as new data appears on the chart. Comparisons can be made between different value combinations. Some guess-and-check values may be tried, but ultimately the tuning procedures discussed in the lectures should be followed demonstrating to students the importance of following these procedures.

StableCAT can also be useful to illustrate additional physics or engineering topics such as lever arms and moments of inertia. Below are some examples of possible lab exercises that can be run with the StableCAT:

- Gyroscopes
- Accelerometers
- Moment of inertia
- Stepper motors
- Arduino programming
- PID algorithms
- PID tuning

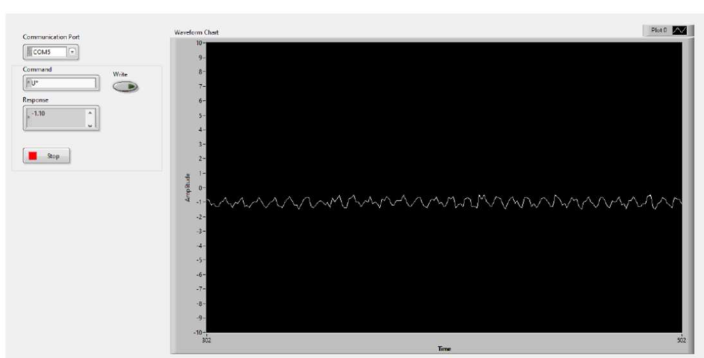

Figure 15: StableCAT in action (monitored by LabView)

3.4 Floating ball trainer

3.4.1 Construction

Unlike the other trainers mentioned above, instead of designing and building the hardware for this trainer, it was purchased from [43]. It cost around $800, a fair price for a package that included a tube, fan, distance sensor, electronic damper as well as a manual damper, a front panel with banana plugs, control buttons and displays, and an Arduino control system designed to simplify the interfacing with PLCs.

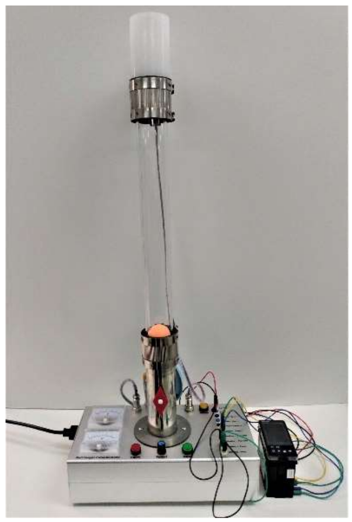

Figure 16: Floating ball trainer with an industrial PID controller

3.4.2 Operation

As mentioned above, the floating ball trainer was originally designed to be controlled by a PLC. It was deemed much too restrictive, and was adapted so it could also be controlled by any 0-10 V source, e.g. OpAmps, external microcontrollers, or LabView / MATLAB / Simulink with appropriate IO. To make sure it could be operated as a stand-alone system as well, an industrial 0-10V PID controller from [44] was also added.

Similar to the inverted pendulum, the primary objective of this trainer is to help teach various PID control topics as well as PID tuning procedures.

Some example lab topics:

- PID control
  - With industrial PID controller
  - with OpAmps
  - with microcontrollers (e.g. Arduino)
  - With LabView / MATLAB / SIMULINK
  - With PLC
- PID tuning procedures

4. Discussion, conclusions, and future work

To recap, preparing students for jobs in the process control industries by teaching practical instrumentation and control courses can be difficult if not impossible without appropriate lab equipment. Traditional solutions involve purchasing and installing Interactive Plant Environment (IPE) systems or more compact process control trainers (PCT). Both are hugely expensive and often require labs to be performed in large groups as opposed to more individualized instruction. In addition, while attempting to combine multiple processes into one training system the manufacturers sometimes fall into a proverbial "jack of all trades, master of none" trap where the individual systems do not perform satisfactorily. Therefore, the authors set out to design and build small scale, inexpensive, and modular process control trainers suitable for teaching specific learning objectives.

Noting the lack of available temperature control trainers, a low-power temperature trainer as well as a high-power temperature trainer were designed and built to help teach temperature process control topics. For teaching PID topics, an inverted pendulum and a floating-ball trainer were built or adapted from existing designs. Whenever possible, industrial grade equipment was utilized, to prepare students to program, commission, calibrate and troubleshoot equipment that they will likely encounter in their future jobs.

Now that the prototyping phase is finished, the next step will be building several more trainers, most of them with some improvements. For the low-power temperature trainer, the cooling fan circuit needs to be debugged as it does not operate reliably. For the inverted pendulum trainer, it might be worth exploring other types of motors (besides stepper motors) to reduce oscillations.

The floating ball trainer still needs the most work. The included Arduino-based PLC interfacing circuit introduces a large lag-time into the system, which makes controlling the floating ball very difficult. One option might be to keep the hardware and completely redesign the signal conditioning and interfacing part of the trainer.

Overall the projects were successful, and greatly enhanced the theoretical aspects of instrumentation and control courses at K-State Salina. As stated in section 1, the objective of this paper was to give readers new and/or improved ideas about designing, building and utilizing various lab equipment to optimize the teaching of instrumentation and control classes, and the authors are pleased to be able to share their projects with a large audience of engineering educators. For questions or comments, please contact them at either eplett@k-state.edu or cnb4966@k-state.edu.

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