# Active Learning Experiences with Embedded Systems, Instrumentation, and Control within and Outside the Classroom

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## Abstract

The "Smart Farming" project supported by the National Institute of Food and Agriculture (NIFA/ USDA) and the "AIRSPACES: Autonomous Instrumented Robotic Sensory Platforms to Advance Creativity and Engage Students" project sponsored by the Maryland Space Grant Consortium (MDSGC/NASA) have facilitated engaging engineering and other STEM students on campus in experiential learning and research efforts in mechatronics and embedded systems applications. Sensing, actuation, and control are integral to smart devices with embedded microcontrollers. Arduino and Raspberry Pi microcontrollers and single-board computers can be interfaced with various sensors and actuators and incorporated into mechanical devices to perform a variety of intelligent functions using appropriate software programming. Over and above the multidisciplinary graduate and undergraduate students that are hired to advance the proposal objectives, project assignments integral to "Instrumentation" and "Control Systems" courses offered by the principal author to juniors in the engineering program endeavor to integrate the out-of-classroom field and laboratory efforts with the course requirements to introduce a larger pool of students to growing efforts in this field. In addition, the use of take-home kits in the project assignment based on Arduino microprocessor boards allows students to engage actively and connect theory to practice on a flexible schedule. Highlights from the course project assignments, the involvement of an engineering student team with NASA's "Rock-On" program, and other recent educational and experiential learning activities of the funded projects mentioned above will be delineated in this paper. Alignment of these efforts with the ABET outcomes and enhancement of the overall educational and university experiences of students will be outlined.


## 1.0 Introduction

The interdisciplinary field of robotics, control, and mechatronics transcends artificial disciplinary boundaries and provides an avenue to integrate knowledge from various fields. Traditional fields within engineering such as mechanical and aerospace, electrical and computer engineering/science, and fundamentals of communications, electronics, information technology, and mathematics, blend seamlessly into developing modern robotic devices with applications in manufacturing automation, space, and underwater exploration, hazardous waste handling and environmental stewardship, agricultural automation and remote sensing, security and defense, medicine and healthcare, and variety of other applications. The resurgence of robotics in manufacturing automation and its potential impact on job creation, and growing applications of ground-based and aerial robotics for applications in space and earth system sciences as well as precision agriculture and environmental stewardship are aligned with the NASA and USDA educational and research objectives, the land grant mission of University of Maryland Eastern Shore(UMES), workforce development undertakings, and the goals of the "Smart Farming" and

"AIRSPACES" projects ongoing on campus for the past several years. Since their inception, these projects have embraced the experiential learning paradigm within a multidisciplinary vertically integrated project framework [1, 2]. Undergraduate engineering and computer science students, as well as other STEM majors, have worked alongside graduate student(s) in the doctoral program in Food Science and Technology (FDST) to advance the project goals under advice from the principal author (also the principal investigator for the projects), as well as other collaborating STEM faculty members on campus.

The "Smart Farming" project efforts are very broad and encompass applications of advanced automation, geospatial information technologies, and remote sensing for sustainable intensification of agricultural productivity [3]. There are aspects of the project related to the development of a robotic boat to collect water quality data, a ground rover to collect agricultural field data at specified waypoints, and utilization of state-of-the-art drones with multispectral cameras to obtain variable nutrient and water needs in row crops [4] that provide avenues for active learning outside the classroom related to Instrumentation and Control Systems courses offered for the engineering undergraduates on campus. Also, soft robotics, small mobile robotic platforms with embedded microprocessors and sensors, and flexible automation efforts with industrial robotic arms [5], as well as, automated farming of specialty crops using 3-axis Cartesian robots (FarmBots) serving small raised beds [6] provide opportunities for experiential learning and educational activities incorporated in the AIRSPACES and "Smart Farming" efforts. These efforts are largely executed from the robotics laboratory in the engineering and aviation sciences building on campus and provide excellent avenues for exposing engineering majors to hands-on aspects related to "Instrumentation", "Control Systems", and "Robotics" courses in the engineering curricula offered by the principal author. While some engineering and STEM undergraduates are hired to work on aspects of these projects as research assistants, integrating some of the project requirements in these courses with the ongoing efforts provides enriching experiences for a larger pool of the engineering student body. In this paper, we will mostly focus on the project efforts integrated with the "Instrumentation" and "Control Systems" courses.

## 2.0 Overview of the Instrumentation and Control Systems Courses and Project Assignments


Figure 1: Grove Starter Kit for Arduino

Instrumentation and Control Systems courses are offered in sequence to engineering majors at UMES. The instrumentation course covers basic principles of measurement and sensor applications to measure different physical phenomena, calibration, aspects of noise measurement and signal conditioning, data acquisition, recording, and presentation. The course also introduces students to the role of instrumentation and sensors in feedback control. Besides course lectures, to provide hands-on learning experiences the students are provided with a popular microprocessor board (Arduino UNO) with add-on sensors & actuators kit to complement the course lectures (see Figure 1). Students receive guidance with the basics of the microprocessor board and its peripherals for analog and digital inputs and outputs. As an integral component of the project, the students are also encouraged to participate in extramurally funded educational projects in the robotics lab and experiential and research efforts in collaboration with graduate students in the Food Science and Technology (FDST) doctoral program in the areas of mechatronics for smart farming and digital agriculture. Interested readers are encouraged to go over reference [7] for more details on the Instrumentation course and the active learning projects integrated therein.

The Control Systems course at UMES builds on fundamentals of differential equations, engineering mechanics (dynamics), sensors/instrumentation, and basic circuit courses and introduces students to mathematical modeling, analysis, and design of controllers for dynamic systems from electrical, mechanical, fluid, and thermal systems. Laplace transform, block diagram, signal flow graph, frequency and time domain characteristics of the system response, stability, root locus, Bode plots, design of compensators based on specifications in time and frequency domains, and PID controllers are covered. The MATLAB control systems toolbox and Simulink are also introduced to the students and incorporated into the project assignment in the course. It has been observed in the past that students have difficulty dealing with the complexity of control theory in abstraction. A take-home kit without too many bulky components such as the Temperature Control Lab(http://apmonitor.com/pdc/index.php/Main/ArduinoTemperatureControl) developed at Brigham Young University was determined to be ideal for introducing students to get exposure to the practice of control engineering experientially without incurring a lot of expense. The kit has been used for undergraduate engineering education effectively at several other universities in the US and abroad [8] and allows students to learn fundamentals of modeling, estimation, and control while using Matlab and Simulink software tools over an Arduino-based platform. The TCLab comes as a shield over Arduino UNO/Leanardo and a couple of transistors is used as heaters and is associated with two temperature sensors (see Figure 3). Interested students can also learn Python, and get an introduction to machine learning using the TCLab kit. Including the TCLab kit as part of the Control Systems course class project and the familiarity of the students with the

Figure 2: Temperature Control Lab (TCLAB) Kit (Arduino based)

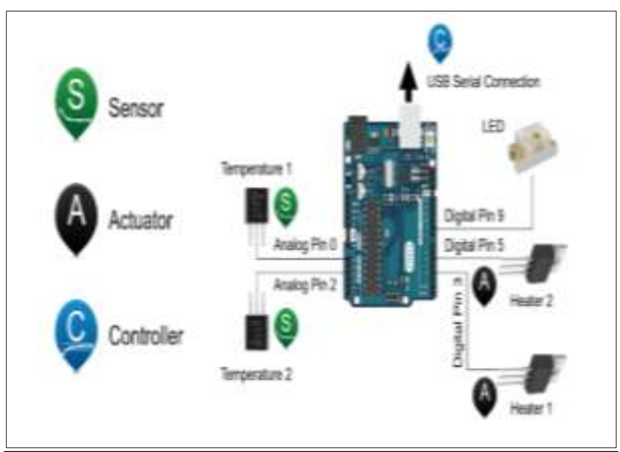



Figure 3: Temperature Control Lab (TCLAB) Sensors and Actuators

Arduino Kit introduced in the Instrumentation course project fit very well with the framework of a spirally bound curriculum [9]. Besides the TCLab as in the Instrumentation course project, the students in the Control systems course are also encouraged to participate in experiential learning and research efforts in the areas of agricultural automation, robotics, and embedded systems integral to the "Smart Farming" and "AIRSPACES" projects. Interested readers can find the assigned Control Systems course project in 2022 spring by clicking on the URL Project Outline.

## 3.0 Highlights from Rock On, TCLab, and Active Learning Projects in the Control Systems Course

While all students have benefitted extensively from the active learning aspects of the Instrumentation course as outlined in reference [7], a few have also volunteered to participate in the NASA Rock On project. More information on the project is available at the URL https://www.nasa.gov/sounding-rockets/rocksat-programs/rockon. It may be noted that the Rock-On project will be implemented within the NASA Wallops premises in 2023 summer, as was the usual practice before the pandemic, but for the last couple of years (2021 and 2022), the payload assembly was carried out remotely with online instruction and video communication from a faculty member at Colorado State University who leads the effort. Students were provided the kit in late spring and they had to complete the payload assembly in early summer. The functional student payloads are incorporated in a NASA-sounding rocket to be deployed in space for taking atmospheric measurements. The typical payload includes Arduino-like microprocessor boards with appropriate sensors that are put together by student teams from several universities. Few of the functional payloads are selected by lottery and flown on sounding rockets and the others are flown on high-altitude student balloon platforms at the NASA Goddard's Wallops Flight Facility (HASP https://www.nasa.gov/centers/wallops/education/students/opportunities/hasp/index.html). During the pandemic, the UMES students found the virtual framework convenient, participated in the Rock-on efforts, and put together functional payloads. In 2021, the UMES payload was not selected by the lottery draw and was flown on a HASP, however, in 2022, the payload put together by UMES students flew on the sounding rocket and a few of the participants also witnessed the rocket launch at Wallops. The students were also provided with the data collected by the payload. Figure 4 provide highlights of the UMES students' Rock On experience last year. The familiarity with the Grove Arduino Sensor Actuator kit introduced in the Instrumentation course went a long way towards overcoming some of the initial hesitations among the students. As shown in the figure the payload UMES students built consisted of a Geiger counter, an Arduino integrated space shield, an accelerometer, a gyroscope, and pressure,

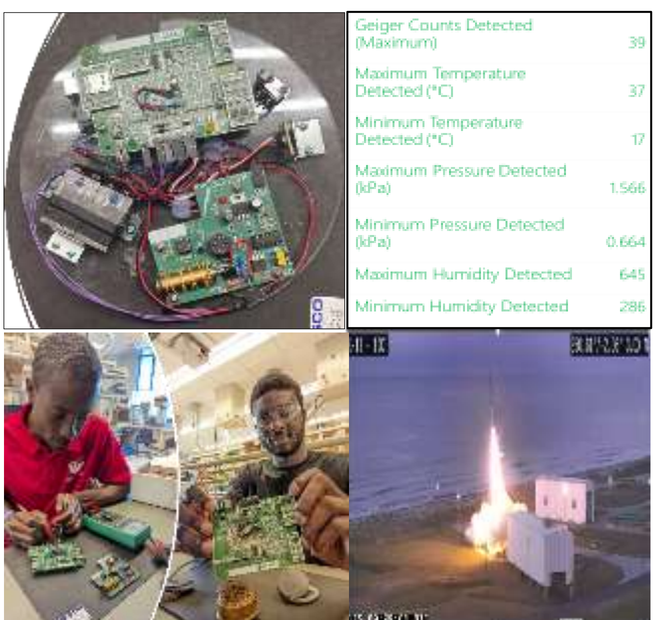



Figure 4: NASA Rock-On Payload and Launch

temperature, and humidity sensors. A 9-volt battery powered the Arduino and it recorded data on an SD card integral to the payload. Figure 4 shows a couple of UMES juniors assembling the payload in the UMES robotics laboratory, a photograph of the sub orbital Orion rocket on which it was launched at NASA Wallops Flight Facility, and some of the data collected by the payload.

Figure 5: Robotic Boat Way Point Tracking (PID)

Figure 6: UGV path tracking without (left) and with PID tuning (right)

Besides the Rock-On project as mentioned in reference [7] the students in the Instrumentation course are also encouraged to get involved with the integration and calibration of water quality sensors on a robotic boat and soil nutrient and photo-synthetically active radiation sensor on a small robotic ground vehicle under development in the UMES robotics lab. The sensors are interfaced on Arduino microprocessor boards and are programmed to collect geo-located data at specified waypoints. Furthermore, these platforms utilize the PIXHAWK autopilot board and the students in the Control Systems course can get hands-on experience with tuning proportional-integral-derivate (PID) gains to navigate the platforms accurately to specified waypoints using GPS and compass sensors as illustrated in Figures 5 and 6. The navigation trials for these efforts are logistically involved and are executed outdoors. A graduate student in the FDST doctoral program works with the participating undergraduates. The boat trials are carried out in the campus ponds or nearby water-bodies and the ground robot trials are carried out in open fields near the engineering building as well as campus agricultural fields.

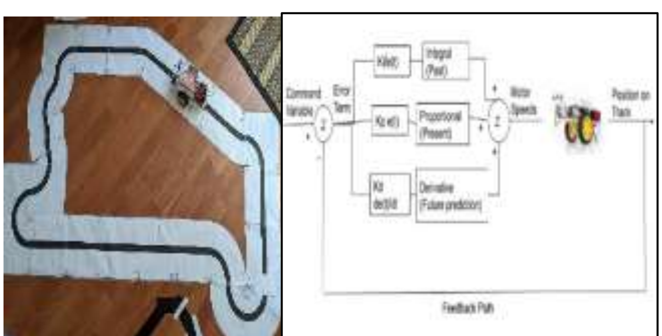
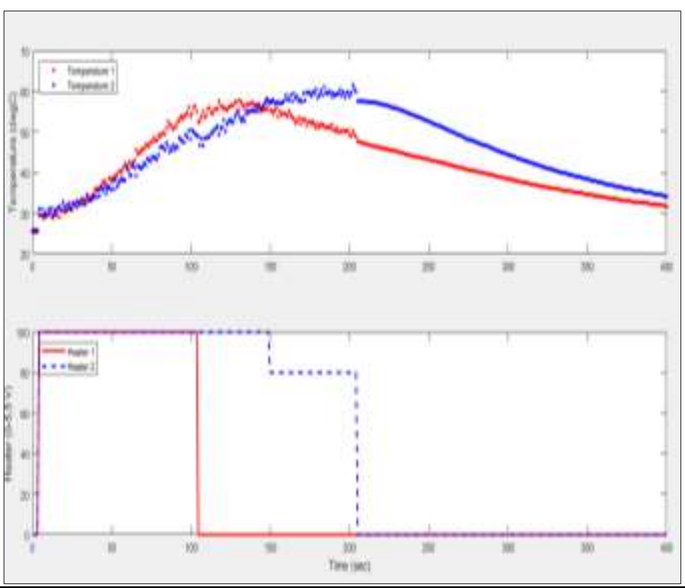


Figure 7: Line Follower Track and PID Controller

A miniature Raspberry Pi-based robotic platform (GoPiGo) is also used for experiential learning activities in the robotics lab. As illustrated in Figure 7, the platform is equipped with a light sensor and can be programmed to follow a track marked in black over a white surface using PID control. A gain-scheduling controller has been developed which allows the user to specify the speed of motion of the robot and the intelligent controller automatically picks suitable PID gains to track the path. The GoPiGo robot provides a demonstration platform for exposing students in the Control Systems course to a practical sensor-based feedback control system that they can easily relate to, as well as contribute to in the improvement efforts.

While the platforms discussed above are excellent for hands-on experiential learning activities and the students in the Control Systems course are encouraged to participate in their development, the logistics and time commitments are involved, hence other than paid student undergraduate assistants, involvement with these efforts is included in the project assignment as “extra credit” options for motivated individuals. The required components of the project assignment include simulation projects using Matlab Control Systems Toolbox and Simulink. Understanding system response, controller design, and stability using commands such as impulse(), step(), lsim(), series(), parallel(), feedback(), rlocus(), bode(), sgrid(), margin(), etc. Basic comprehension of PID controllers, Ziegler Nichols tuning rules, and Simulink fundamentals are also emphasized. The interested reader can look over the [project outline](project outline) for more details.

Hands-on active learning activities with the TC lab kit (Temperature Control Lab) have also been included as a required component of the project work in the spring 2022 and 2023 (ongoing) project requirements in the course. The students are encouraged to work in teams and explore all aspects of the kit, however, since some facets of the kit are beyond the scope of the course, students in the course are only required to familiarize themselves with the basics of MATLAB and Simulink implementations of a SISO (single input single output) system using a single heater and a temperature sensor. Students are also instructed to download appropriate components for TCLab from MATLAB central file exchange [10].



```
close all; clear all; clc
% include tclab.m for initialization
tclab;
disp('Test Heater 1')
disp('LED Indicates Temperature')
figure(1)
t1s = [];t2s = [];h1s = [];h2s = [];
% initial heater values
ht1 = 0;ht2 = 0;h1(ht1);h2(ht2);
for i = 1:399
    tic;
    if i==5
        disp('Turn on heater 1')
        ht1 = 100;ht2 = ht1; h1(ht1);h2(ht2);
    end
    if i==105
        disp('Turn off heater 1')
        ht1 = 0;h1(ht1);
    end
    if i==150
        disp('Turn on heater 2 to 80%')
        ht2 = 80;h2(ht2);
    end
    if i==205
        disp('Turn off heaters')
        ht1 = 0;ht2 = 0; h1(ht1); h2(ht2);
    end
    % read temperatures
    t1 = T1C(); t2 = T2C();

    % plot heater and temperature data
```

Figure 8: Portion of Matlab Script for test_Heaters.m (right) and the corresponding display (left)

The campus license for MATLAB allows all students to download the basic software and its toolboxes on their laptops/desktops alleviating the logistics issues. Once all the Arduino and TCLab-related add-ons are also installed, it becomes easy for students to plug and play with the kit. At least two USB ports are necessary to power the Arduino and heaters from their laptop. After all the hardware set-up is completed, the students can experiment with the kit using MATLAB and Simulink code that is also provided for download by the developer. Besides MATLAB students can also choose to use Python if they so desire but for the course project, the students were only recommended to use MATLAB and Simulink.

At the minimum students are required to execute the test_Heaters.m script file ( a portion of it is shown in Figure 8 to the right) and Simulink PID control implementation for single output single input(SISO) set up using just one heater and sensor (shown in Figure 9(left)) available for download from the TCLab website. As shown in the code in Figure 8, Heater1 turns on at full power (100%) at the 5$^{th}$ iteration of the for loop and turns off at the 105$^{th}$ iteration, while Heater 2 turns on at 80% of full power at the 150$^{th}$ iteration and turns off at 205$^{th}$ iteration. The temperature sensor data associated with the heaters are read and displayed on the subplot on top along with the heaters' on-off status during program iterations on the bottom (Figure 8).

Since there are two heaters and two temperature sensors in the kit it is possible to implement MIMO (Multiple Input Multiple Output) control implementation with the setup and explore other advanced control algorithms. However, the objective was not to overwhelm the junior-level undergraduate students but to allow them to get a practical and readily observable active learning experience that brought home some of the theories that they learn in the course. As such, a SISO implementation was considered adequate, but the students were encouraged to use different desired setpoints and PID gains and observe the results. They were also encouraged to observe open loop (no feedback) responses due to inputs such as "step" and other inputs readily available in the Simulink environment.

PID control results (orange) for a set-point temperature of 60$^0$ C (yellow) are shown for ready reference in Figure 9 (right) with the corresponding Simulink code Figure 9 (left).

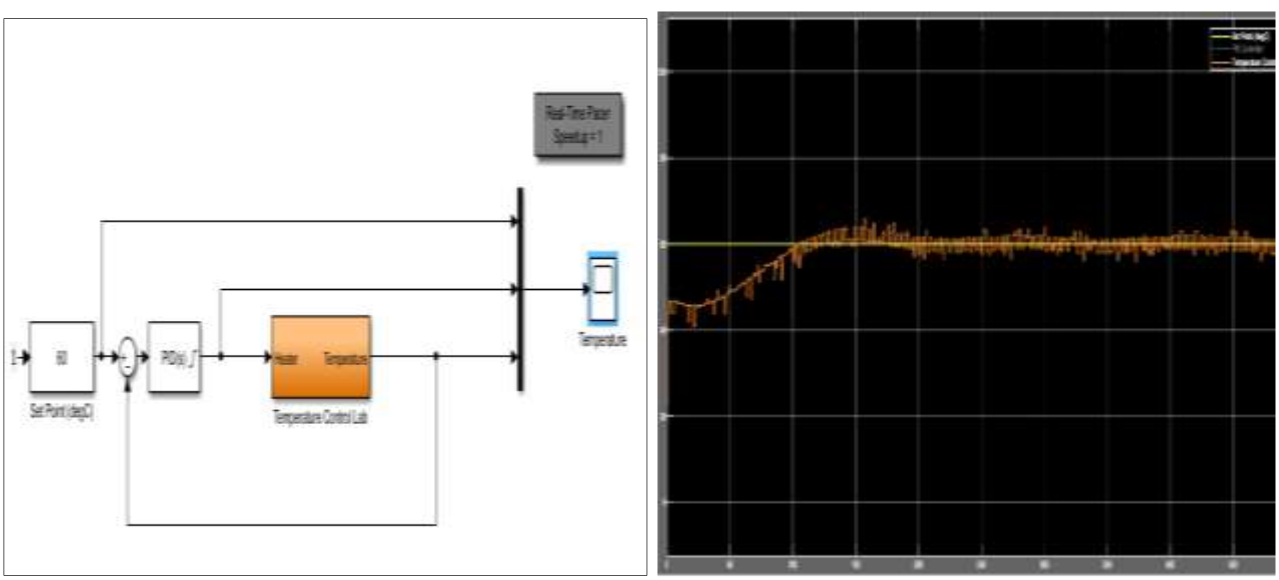



Figure 9: Simulink implementation of PID with TCLab(left) and the corresponding results (right)

## 4.0 Assessment and Learning Outcomes

Learning can be categorized into developing skills in the cognitive, affective, and psychomotor domains. Higher education focuses largely on the cognitive domain following Bloom's taxonomy – knowledge, comprehension, application, analysis, synthesis, and evaluation [11]. ABET outcomes for engineering education integrate developing student abilities in both the affective domain by emphasizing soft skills and the cognitive domain by promoting critical thinking and creativity [12]. While lecture-based instruction is essential from the point of view of delivering content knowledge appropriate for an engineering curriculum, blending active, cooperative, and problem-based learning with course lectures reinforces the development of higher-order skills of application, analysis, and synthesis. In lecture-based instruction, the teacher is active and students are passively listening and trying to take notes and comprehend the material being taught. As outlined in the reference [5] incorporating active and project-based learning enhanced educational experiences for students in the Instrumentation course. The inclusion of the Temperature Control Lab Kit reinforces student familiarity with Arduino as well as develops MATLAB and Simulink fundamentals. The kit also introduces students to digital controls that will follow. The ABET learning outcomes related to teamwork, analyzing and interpreting data, and self-directed acquisition of new knowledge was facilitated by problem-based learning exercises and project assignments.

Lastly, the extra credit options allowed the undergraduate students to get involved with ongoing extramurally funded experiential learning and research projects and provided them some flavor, albeit limited, of the relevance of the course material in the broader context. In addition, in a limited way, the extra credit-driven involvement of the undergraduate students advanced the goals of the ongoing funded projects led by the primary author and provided support to the graduate student engaged in the efforts delineated. The activities also provided a window into the broad overlaps of NASA's earth and space science undertaking, the sustainability efforts of NIFA, the land grant mission of the campus, and their common educational objectives and workforce development goals.

## 5.0 Acknowledgment

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