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Automation Course and Laboratory on Design and Programming of Multi-axis Industrial Machines

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Abstract

Automated machinery used in industries including packaging, assembly, textile, paper, electronics, food processing rely on advanced motion control. To design such systems, engineers need to be familiar with industrial motion controllers, bring together knowledge from kinematics, control theory, dynamics, electronics, machine design and programming. Mechanical engineering programs have developed courses and laboratories in controls and mechatronics. These courses mostly rely on specialized laboratory equipment, LEGO robots, board-level electronics, interfacing and microprocessor programming. The industry expectation is more about system integration, selecting components from industrial product catalogs, calculations to match design requirements and programming of multi-axis motion controllers. In this paper, a senior-level Automation course with laboratory is presented. Lectures present design of automated machinery through industrial component selections and through software design for integration. The laboratory has several miniaturized, simplified machines representing various industrial sectors. The paper explains the course content, the machinery and the weekly laboratory exercises. Assessment results from multiple offerings of the course are also discussed. This project was funded by a grant from the NSF-DUE.

1 Introduction

The academic community has made significant advances in developing educational materials and laboratory exercises for fundamental mechatronics and controls education. Students learn mathematical control theory, board-level electronics, interfacing and microprocessors supplemented with educational laboratory equipment[1,2,3] The current curriculum tends to have a compartmentalized approach with separately taught subjects of abstract control theory, kinematics, dynamics, electronics, programming and machine design. The educational laboratory equipment such as balancing an inverted pendulum or a ball-on-beam, LEGO robots following lines or solving a maze are some examples. We use these platforms and heavily mathematical content to “teach the fundamentals” and let them learn the industrial hardware after graduation.

As new mechanical and electrical engineering graduates become practicing engineers, many are engaged in industrial automation projects. Knowledge of industrial motion control technology is an absolute must since industrial automation is designed primarily around specialized motion control hardware and software. Industry needs engineers who can do system design and integration using motion controllers and Programmable Logic Controllers (PLC) as the primary building blocks for automation/mechatronics applications. They are not expected to *design* controllers, control algorithms or interface electronic circuits at the board level or program microprocessors such as Arduino[4,5]. Instead, they need to combine theoretical and practical knowledge to select industrial-grade components from manufacturers' catalogs. The practicing automation engineer needs to be able *integrate* various components such as gearbox, transmission elements, motion controller, I/O cards, sensors, control devices and be able to program the controller using a high-level language to build an automatic machine.

In this paper, we present a senior-level Automation course and its laboratory to address the gap. The novelty of the course is the balanced coverage of industrial practices and theoretical content using industrial components, manufacturer data sheets and catalogs. Theoretical calculations for sizing motors, gearboxes and other components are presented. Operating principles of drives and control hardware are explained in detail. This is balanced by hands-on programming experiences in the lab focusing on programmable logic controller (PLC) and multi-axis motion controller programming. The finite state machine programming technique for PLC programming is introduced. While fundamental theory of PID motor position controllers is reviewed in lectures, practical tuning of the PID controllers embedded in the motion controller of the lab machines is explored by the students. The course and laboratory content were determined after many discussions with engineers in the motion control industry. The paper explains the course content, custom-built laboratory machines and lab exercises in detail. Assessment results from multiple offerings of the course are presented.

2 Curriculum

The curriculum has been implemented in the Mech 467 Automation course at Washington State University Vancouver . This is a senior-level elective course, which is part of our mechatronics option track. It is a 3-credit semester course with two 50-minute lectures and a 150-minute laboratory per week. The course attracts students from mechanical and electrical engineering programs. Typical enrollment is about 30 students.

The context of studying industrial motion control systems naturally brings separately taught topics together and often crosses disciplinary boundaries. The curriculum content came from the author's experience in developing and teaching mechatronics and automation courses, working with undergraduate students and from many discussions with engineers in the motion control industry. The aim was to provide a balanced coverage of theory and practical concepts.

Much of this material is available in manufacturer data sheets, product catalogs, fragments in various college courses, websites, trade magazines and as know-how among practicing engineers. The curriculum presents these pieces in a cohesive way to provide the fundamentals while supplementing them with solved examples based on practical applications. The course content closely follows a textbook written by the author[6]. The book contains all the lecture materials, example design problems, and theoretical and practical details of automatic machinery[7].

Module 1 Introduction - (1 lecture) is an introduction of the building blocks of a typical motion control system. The functionality of each block, such as the user interface, motion controller, feedback sensors, is briefly introduced followed by example hardware used in industry to build these blocks.

Module 2 Motion Profile - (3 lectures) examines how the motion profile is generated when an axis of a machine makes a move. After an overview of basic kinematics, trapezoidal and S-curve velocity profiles are explained.

Module 3 Drive-train Design - (7 lectures) is on mechanical design of a motion axis. It primarily concentrates on proper selection of a motor and gearbox to meet the desired motion profile requirements of the axis. Concepts of inertia reflection, torque reflection and inertia ratio are introduced. Five types of transmission mechanisms are explored in depth. Torque-speed curves of motors, gearboxes and motor selection procedures for different types of motors and axes with transmission mechanisms are provided.

Module 4 AC Servomotors - (1 lecture) is a review of AC servomotors, which are the most common type of motor used in automatic machinery. Construction and operational details of AC servo and induction motors are provided. Torque generation performance of AC servo motors with sinusoidal and six-step commutation are compared. The chapter concludes with overview of mathematical and simulation models for both types of motors.

Module 5 Sensors and Control Devices - (2 lectures) reviews sensors and control devices used in building automatic machinery. Various types of optical encoders for position measurement, limit switches, proximity sensors, photoelectric sensors and ultrasonic sensors are presented. Sinking or sourcing designations for sensor compatibility to I/O cards are explained. Next, control devices such as push buttons, selector switches and indicator lights are presented. The module concludes with an overview of motor starters, contactors, overload relays, soft-starters and a three-wire motor control circuit.

Module 6 AC drives - (7 lectures) A drive amplifies small command signals generated by the controller to high power voltage and current levels necessary to operate a motor. The module begins by presenting the building blocks of drive electronics including the pulse width modulation (PWM) control technique. Then, basic closed-loop control structures implemented in the drive are introduced. Single-loop PID position control and cascaded velocity and position loops with feedforward control are explored in depth. Mathematical and simulation models of the controllers are provided. Control algorithms use gains that must be tuned so that the servo system for each axis can follow its commanded trajectory as closely as possible. The module concludes by providing tuning procedures for the control algorithms presented earlier and includes practical ways to address integrator saturation.

Module 7 Motion Control Applications - (2 lectures) concludes the course, which is about certain programming and typical motion control applications. Many industrial motion control applications involve coordinated moves of multiple axes. Techniques such as set-point command, master/slave axes coordination, ratio following, electronic gearing and camming are introduced. Typical industrial applications including spool winding, flying saw, rotating knife and web tension control are discussed.

2.1 Research project

A research project is used as a way to bring the "big picture" of automation into the course. This exercise is different than a typical technical research project a graduate student might conduct. It is rather about finding information on specific technologies, trends or policies to answer the questions on the assignment. The goal is to create interactive lectures to discuss emerging technologies that can be used in automation as well as potential impacts on the workforce and society.

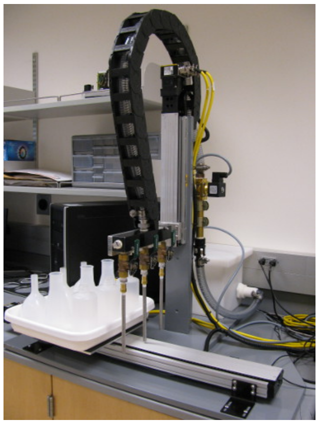
The instructor selects 6 contemporary topics such as Made in China 2025[8], augmented reality[9], ManufacturingUSA Institutes[10], artificial intelligence, Internet of things[11] and Industry 4.0[12]. Each student is assigned one of these topics. Each student is required to prepare a short PowerPoint presentation (5 slides) and a 1-page report to explore four questions given by the instructor. At the end of the semester, two lectures are used for student presentations. Each lecture can accommodate three 15-min presentations. The instructor randomly selects a student from each topic to make a class presentation using his/her slides. All submitted reports and slides are graded using a rubric (Appendix). But the oral presentation is not part of the grade since not all students can present. They all come ready to the class to present but may not be selected. Over the years it has been interesting to observe that often students volunteered to present because they were excited about their findings and wanted to share with the class.

3 Laboratory

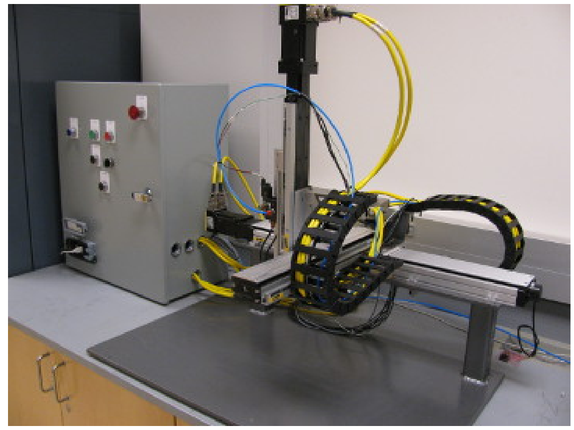
The course has weekly 150-minute laboratory session. The primary goal of the laboratory is to provide hands-on programming experience with an industrial motion controller. Students also learn about details of how the lab machines were built, including wiring, various sensors, devices, motors, etc. used in the systems. Some of the modules give them a chance to explore concepts learned in the lectures. Other modules, such as the PLC or finite state machine programming, are additional materials introduced only in the lab with hands-on experience.

The laboratory has six stations (Figure 1)[7]. These machines were designed and built by a team of ten undergraduate and graduate students under the supervision of the author. They were hired as research assistants during the new course development effort over a period of two years. Each machine has a control panel (Figure 2) that is similar to typical panels found in industry. But the machines are miniaturized, simplified versions of the real industrial machines. All systems were built using industrial-grade components. Our machines use Geo Brick 4-axis motion controllers by DeltaTau Inc.[13]. On average, each machine costs about $16,000, including the motion controller, software licenses and a PC. The total cost of the project, including salaries of researchers, students, indirect costs, parts, etc. was about $250K. Some of the costs were offset by donations from industry.

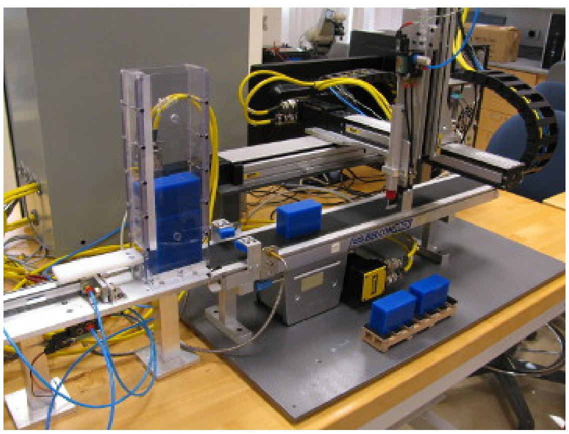
Although the lab stations are different machines, they share common features so that general skills such as jogging axes, I/O mapping, user interface mapping, motion profile programming, etc. are all the same regardless of the machine. Hence, students can use any machine when they



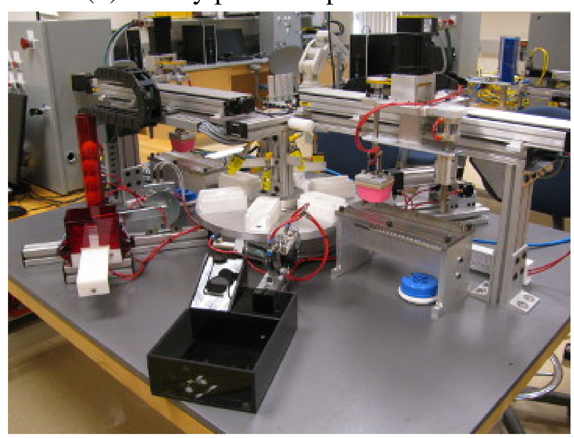
(a) Bottle filling



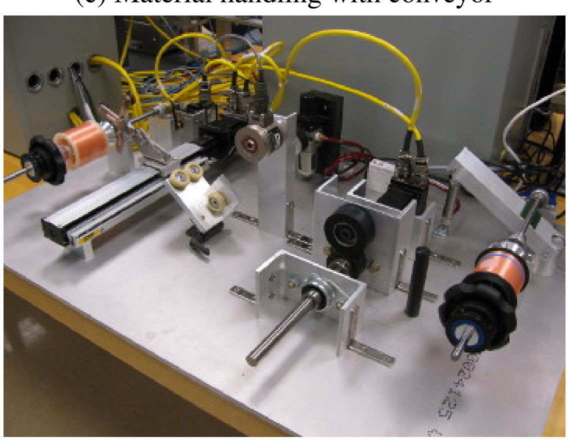
(b) Gantry pick-and-place machine



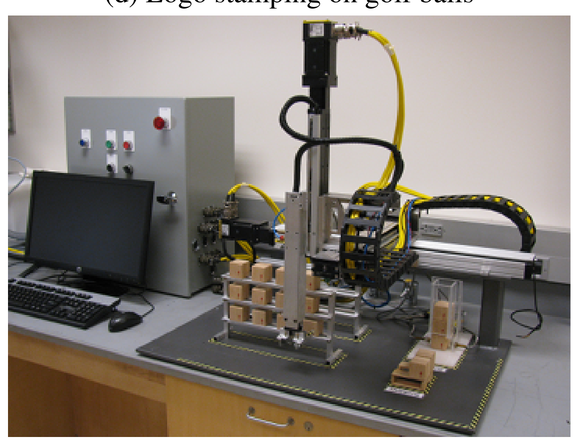
(c) Material handling with conveyor



(d) Logo stamping on golf balls



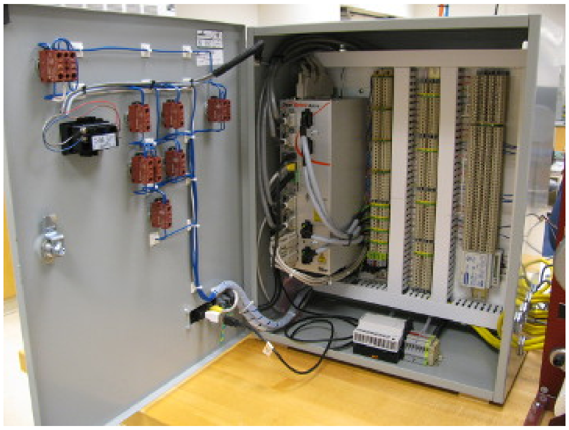
(e) Winding machine for fishing line



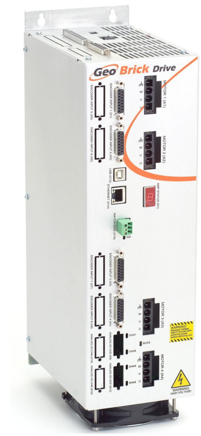
(f) Automated warehouse

Figure 1: Laboratory stations.

come into the lab for modules 1 - 4. Some prefer to always sit at the same machine while others want to try a different machine each week.



(a) Control panel



(b) Geo Brick 4-axis motion controller[13]

Figure 2: Control system for each station.

During the lab, students work in teams of two at each station. Modules 1 - 4 in Table 1 are completed within two lab sessions each. Student pairs work through each module at their own pace with the requirement that the module is finished by the end of the two sessions. Some groups can advance quickly and finish a little earlier than the allocated two sessions. Then, they are given the option of spending the remaining time in the lab to go over parts of the same module, or explore what-if scenarios on their own, or leave. If a group finishes earlier than two sessions, it is not allowed to advance to the next module to keep the entire class in sync.

The overall design of lab modules 1 - 4 is based on the following structure:

1. Instructional content on a specific topic,

Table 1: Laboratory modules.

	Module	Content	No. of lab sessions
1	Manual operation	Activate/deactive motors, open/close control loops, jogging axes, position and machine I/O monitoring	2
2	PLC programs	Basic PLC program structure, enabling/disabling PLCs, sample logic control programs, file organization	2
3	Finite state machines	PLC programming using finite state machines, control logic design, file organization, testing, adding new control features	2
4	Motion programs	Coordinate systems, motion program structure, running/stopping motion programs, multi-tasking with PLCs, sample motion programs	2
5	Lab project	Team project, complete control system programming to fully operate a lab machine	4

2. Examples that walk through step-by-step interactions with the lab machine, and
3. One or more "your turn" exercises where limited details are provided on a task to be completed with the lab machine.

This is similar to a typical textbook where the "your turn" exercises are like the chapter-end problems except these problems must be solved using the lab machines. Students are asked to come to the lab prepared by reading the module and having an initial program design for the exercises in the module. Most of them prepare a draft program at home using a plain text editor and bring it to class to get started quickly with the lab machine. Throughout the lab session, they interact with the instructor and the TA frequently. Details of one of the lab modules, student input and learning gains from the module after the lectures and the lab session were published earlier[14].

Mastery tests - Are short tests given in the lab. One student sits at each station. The test contains one or two questions (sample in Appendix). Students have 20 minutes to complete it. At least one of the questions is about demonstrating some control or programming competency with the lab machine. At the end of the test, the instructor or TA goes to each station and asks the student to demonstrate the skill with the machine. For example, it may require configuring a scaling factor so that an axis motion can be commanded in inches instead of motor counts or it may require writing a small PLC program. The rubric used for the test grading is: 0=not working, 1=some things correct, 2=partially working/correct, 3=mostly working/correct, 4=working/correct.

3.1 Laboratory project

Throughout the semester, students are exploring various things to build up skills and knowledge using the lab machines. For example, they learn how to make an axis move by issuing a command or how to program homing of an axis, etc. Each of these activities require using *parts* of the machine.

At the end of the semester in module 5, student teams are assigned to lab machines to develop complete control programs to make the entire machine functional. This module takes 4 weeks. Each team is given a portion of the control program but various parts are missing. These are the parts student teams need to complete. During these 4 weeks, many interactions take place between the students and with the instructor and the TA. Many trial-and-error ideas are explored on the lab machines. Student teams get together outside the lab to work together to continue to develop their programs using a simple text editor. Then, they bring it to the lab and quickly test it on the lab machine. In the end, each team gives a demonstration of their machine to the class. Each team also submits a 2-page project report highlighting the main ideas behind the code sections they developed. In the first session, each team also develops a Gantt chart for the project, including milestones and deliverables.

4 Results

The course has been offered in this format since 2013 except for Fall 2020 due to closure of the university laboratories during the pandemic. In each offering, two mastery tests were given in the lab after modules 2 and 4 in Table 1. As seen in Figure 3, most students can demonstrate a working solution or get close to it during this brief test. Some of the variation in the scores from year-to-year can be attributed to the programming skills of the students in the class in a given year. Some mechanical engineering students have a better grasp of fundamental programming concepts than others. Even though they learn the underlying technical concepts taught in the lab, some cannot demonstrate their programming skills in a short test setting.

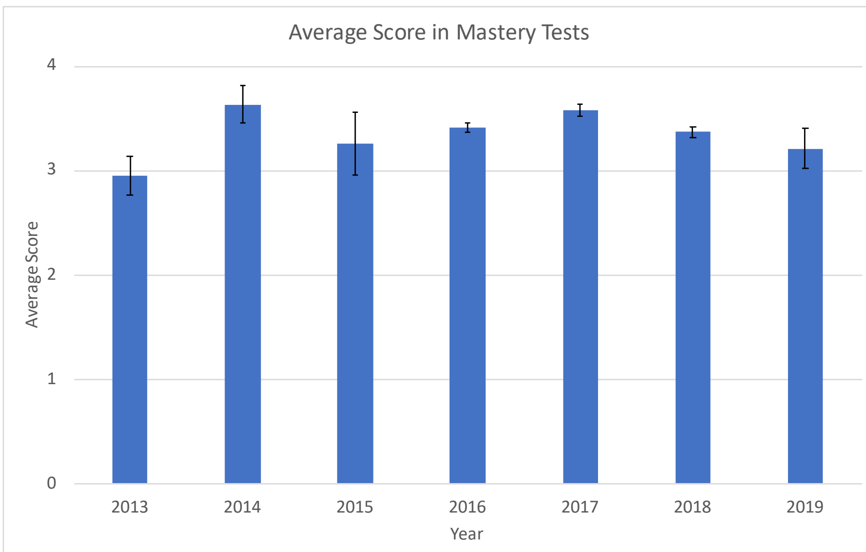


Figure 3: Results of mastery tests in the lab (2013 - 2019).

In our program, course outcomes are derived from the ABET a - k student learning outcomes at the program level. Details of the process, rubrics, and assessment of outcomes using specific questions on assignment were published separately[15]. In the 2013-2017 academic years, the course had the following outcomes:

- B-4: Validate motion performance of a multi-axis lab machine
- E-3: Select components for motion systems
- K-2: Write motion and PLC programs and simulate system response
- K-4: Use MATLAB software for controller tuning

Figure 4 shows average course outcomes assessment results. In each exam and homework, specific questions are used to target specific outcomes. Later, the grades for each student in these specific questions are converted into scores on the 1 - 5 scale (5 highest). For example, in 2014 the average of scores for all students in achieving the E-3 outcome was 4.1. Overall, students did very well on the assignments targeting the K-2 and K-4 outcomes where the scores were around 5.0. These outcomes were on programming. The B-4 and E-3 outcomes were accomplished well as their scores were around 4.0. These outcomes emphasized validation of theoretical motion calculations and implementation of the same motion using the lab stations, and selection of components from catalogs to design automatic machines.

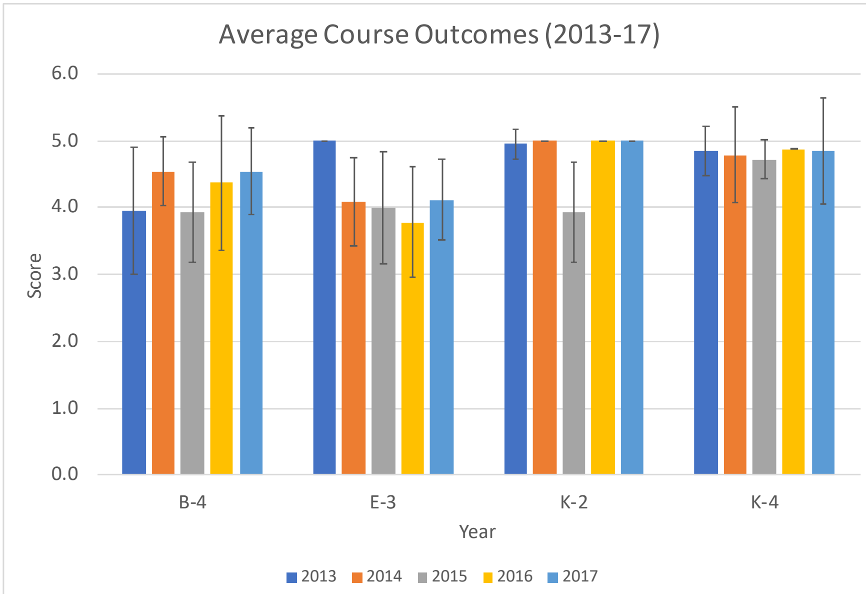


Figure 4: Results of course outcomes assessment (2013 - 2017).

Starting in 2018, our program went through a revision to align all course outcomes with the new ABET 1 - 7 student learning outcomes. As a result, the course outcomes were changed into:

- 1-d: Apply engineering principles to solve motion system problems
- 2-d: Select components for motion systems to meet design specifications
- 5-a: Develop project Gantt chart jointly with team members
- 2-b: Follow specific design procedures to identify components for motion control systems

Figure 5 shows average course outcomes assessment results for the new set. The same assessment process described earlier was used in assignments and conversion into scores on the 1 - 5 scale. Except for the 2-b outcome being slightly lower than 4.0 in 2018, the 1-d, 2-d and 2-b outcomes were accomplished successfully by the students. At this point as seniors, they know how to make a Gantt chart for a project, as shown by the perfect scores for 5-a.

The research project and the in-class presentations were popular. Due to the nature of the topics, students engage in lively conversations. Many students commented about how much they liked this assignment since it gave them a chance to place the technologies they learned in class into a bigger context. They also appreciate that the assignment was not burdensome since it required a short report and simple slides to be submitted.

All teams complete the lab projects successfully. It is interesting to observe the growth in their confidence with the new material and the lab systems through the semester. By the time we start the lab project in the last 4 weeks of the semester, they are competent with the equipment, excited

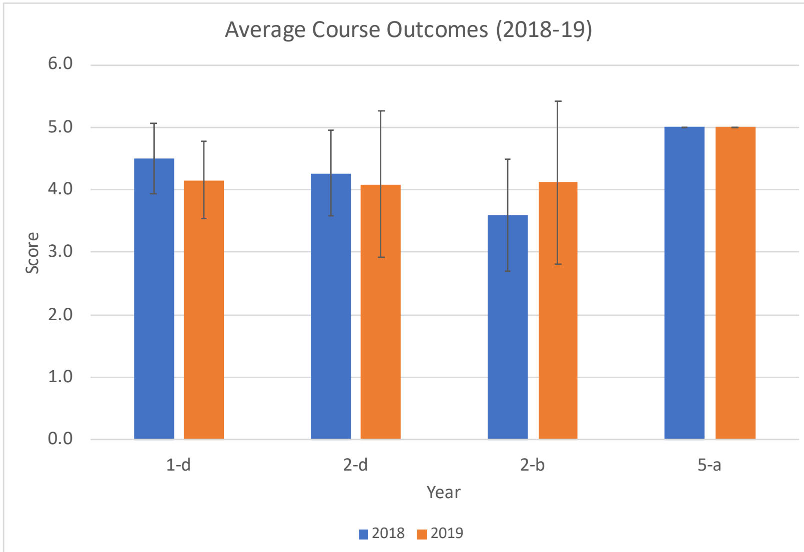


Figure 5: Results of course outcomes assessment (2018, 2019).

and engaged in the project, which leads to successful completion of the projects. Along the way, close interactions by the instructor and the TA are also very helpful to the teams.

5 Conclusions

In this paper, a senior-level elective course on Automation has been presented. The course was designed to address industry needs from a relatively new mechanical or electrical engineering graduate who is involved in industrial automation projects. The course and its weekly labs provide a balanced coverage of theoretical concepts, practical approaches and hands-on experiences. During the lab, students work in teams of two at each station to try to complete a lab module in their own pace. Mastery tests are used as a quick way to assess their skill development and to provide feedback. A popular component of the course is the research project. Even though some students may initially get nervous about presenting to the class, in the end they all get very engaged in the conversations creating a really active learning environment.

Building a laboratory like this is challenging. The machinery are not available off-the-shelf. They are expensive since industrial-grade components and controllers are used in the design to meet the main goal of the course. Programming software is proprietary, expensive and requires license. The student excitement and feedback about the course have been extremely positive.

In parallel to this course, most students are also taking their senior capstone course where some students worked on automated machines for their team project. Feedback from the project sponsors has been very positive indicating that they were able to design custom machines. The controller used was different based on the preferred equipment of the sponsor but students were able to carry out the machine design, interfacing and programming. Finally, over the past few years, several students were hired by local companies for automation engineering positions including by companies that design OEM automatic machines.

Acknowledgments

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References

[1] S. Chandrasekaran and J. M. Long and M. A. Joordens, "Evaluation of student learning outcomes in fourth year engineering mechatronics through design based learning curriculum." IEEE Frontiers in Education Conference (FIE), 2015.

[2] K. Meah, "First-time experience of teaching a project-based mechatronics course." ASEE Annual Conference and Exposition, 2016.

[3] Y. Wang, Y. Yu, H. Wiedmann, N. Xie, C. Xie, W. Jiang, and X. Feng, "Project-based learning in mechatronics education in close collaboration with industry: Methodologies, examples and experiences," *Mechatronics*, vol. 22, pp. 862–869, 2012.

[4] L. Funke, J. B. Hylton, and D. Sawyers, "Work in progress: Incorporating microprocessors across the mechanical engineering curriculum." ASEE Annual Conference and Exposition, 2019.

[5] J. D. Garcia, A. J. Norway, V. J. DuPriest, and C. J. O'Malley, "Engineering design applications in the introduction to mechanical engineering curriculum." ASEE Annual Conference and Exposition, 2019.

[6] H. Gurocak, *Industrial Motion Control: Motor selection, Drives, Controller tuning, Applications*. John Wiley & Sons, 2016, no. ISBN: 9781118350812.

[7] ——, "Robotics and Automation Laboratory," https://labs.wsu.edu/robotics-and-automation/automation/, Accessed April 2021.

[8] Center for Strategic and International Studies, "Made in China 2025," https://www.csis.org/analysis/made-china-2025, Accessed Dec 2020.

[9] T. F. Institute, "What is augmented reality?" https://www.fi.edu/what-is-augmented-reality, Accessed Dec 2020.

[10] Manufacturing USA, "Manufacturing USA Institutes," https://www.manufacturingusa.com/institutes, Accessed Dec 2020.

[11] Forbes.com, "A simple explanation of the Internet of Things," https://www.forbes.com/sites/jacobmorgan/2014/05/13/simple-explanation-internet-things-that-anyone-can-understand/#125bb7f91d09, 2014.

[12] ——, "What is Industry 4.0? Here's A Super Easy Explanation For Anyone," https://www.forbes.com/sites/bernardmarr/2018/09/02/what-is-industry-4-0-heres-a-super-easy-explanation-

for-anyone/#430ff4a59788,
2018.

[13] Delta Tau Data Systems Inc., “Geo Brick Drive,” http://www.deltatau.com/DT_IndexPage/index.aspx, Accessed Dec 2020.

[14] H. Gurocak and A. Ater-Kranov, “New mechatronics curriculum on multi-axis industrial motion control.” Indianapolis, IN: ASEE Annual Conference and Exposition, June 2014.

[15] H. Gurocak, L. Chen, D. Kim, and A. Jokar, “Assessment of program outcomes for ABET accreditation.” Austin, Texas: ASEE Annual Conference and Exposition, June 2009.

Appendix

Mech 467 Automation
Mastery Test

Name : ______________________

Question 1. 4 pt

Axis #1 travels for a total of 1000 msec. Given the velocity profile with I120=100, I121=0, I122=32, I119=0.15625, how long will the axis travel at the I122 speed ? This question does *not* require using the machine. *Show details of your calculations on paper.*

Travel time at I122 speed = __________________ *msec*

Question 2. 4 pt

1. Adjust the position window units so that the *linear travel* of axis #1 is shown in inches (1 in = 25.4 mm). *Show details of your calculations.*

   Cts. Per Unit = ______________________

2. Home the axis.

3. Demonstrate the position reading on the screen by jogging the axis 2 *inches*. What did you type into the TERMINAL WINDOW to move the axis?

   ANS = ______________________

Question	1.	2.	Total
Points	4	4	8
Your Score			

Figure 6: Sample mastery test.

GRADING RUBRIC		Points
WRITING		
	Description of the technology	
	Presented the main ideas of the topic clearly	10
	How will it change automation technology in future?	
	Explained what will change in the current automation technologies	10
	Explained what the future factories may look like	5
	Impact on current workforce	
	Described positive/negative impact on the current workforce	5
	Described resulting impact on the society	5
	What should current workforce do to prepare?	
	Described what the current workforce should do to prepare (to remain employable)	10
	Gave examples of specific topics to study or skills to develop	5
	Writing was easy to understand	5
	Free of grammatical and spelling errors	5
	Complied with the format requirement	5
	Included references	5
	TOTAL:	**70**
SLIDES		
	Title slide complete with author, institution details	5
	Each slide has simple message	5
	Slides were not cluttered	5
	Photos, diagrams (or video) were included to explain things	5
	References were provided	5
	Complied with the format requirement (max 4 slides, plus one for references)	5
	TOTAL:	**30**

Figure 7: Rubric for research project.