Teaching Undergraduate Robotic Courses using Enhanced VEX Robots

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Abstract

This paper summarizes our experience of teaching undergraduate robotic courses in the past ten years. The objective is to introduce students to the fundamental knowledge in robotics. Lecture topics covered subjects in both Autonomous Mobile Robots and Robotic Manipulator. In the lab sessions, students work on physical robots to acquire basic robotic design, integration, and algorithm implementation skills. The commercially-available VEX robotic kits, together with its extensions, are used as the robotic platform. By constructing an autonomous mobile base, students can explore topics pertaining to Autonomous Mobile Robots. By adding a simple robotic arm on top of the mobile base, students can investigate subjects in Robotic Manipulator. By further integrating the VEX robot with other devices such as Raspberry PI (with its camera module) and XBee modules, the enhanced VEX robots achieved onboard image processing and wireless inter-vehicle communication capabilities. More advanced topics, such as vision-based control and coordinated control, can then be brought to the undergraduate robotic classroom, boosting students' interest in robotics and the STEM fields in general. The course learning objectives of obtaining knowledge and skills in both Autonomous Mobile Robot and Robotic Manipulator were assessed using direct assessment methods via in-class exams. Students' acquired hands-on skills and their interests into robotics and general STEM fields were evaluated using indirect methods via surveys and Student Evaluation of Teaching (SETs). The combined assessment results demonstrate the effectiveness of the designed course content, projects, and the overall teaching approaches.

Keywords*—Robotics education; VEX robots; image processing; wireless inter-vehicle communication; robotic network.*

Introduction

Robotics is an important subject in undergraduate education for engineering and technology majors [1]. It is a widely-held belief among researchers and educators that robotics is a good mechanism and aid to teach students Science, Engineering, Technology, and Mathematics (STEM), and the interlacing of all these inter-disciplinary areas [2, 3, 4]. Construction and control of a robot requires knowledge in various STEM fields, i.e., Mechanical Engineering (ME) for designing physical robots; Electrical & Computer Engineering (ECE) for adding electronics, micro-controller, and/or micro-processor as the robot's "brain"; Computer Science (CS) for bringing in higher-level decision making; and Mathematics (application of differential equations, calculus, linear algebra, probability & statistics) for serving as foundation for all these areas. Recent research and development in medical, biomedical, and bio-robotics initiate a strong connection between Science and Engineering & Technology. Since robotics promotes students' interest toward various STEM subjects [5], robotics-related activities have been included into higher education in different formats such as summer camps [6], workshops [7], robotic competitions [8], senior design projects [9], and undergraduate research [10, 11, 12]. Studies show that the support of robotics for STEM education has been successful [13], as demonstrated by increased awareness about the role of engineering [14], increased test scores in science & programming concepts [15], and improved soft skills in leadership, presentation, & time management [16].

Institutions take different approaches to systematically teach robotics in their curriculum. For example, Carnegie Mellon University and Worcester Polytechnic Institute have a dedicated robotics institute or department. Courses offered by these institutions are complete and thorough, covering a broad spectrum of subjects, including mechanical design, electronics, feedback & control, computer vision, machine learning, and human-robot interaction, to name but a few. Duke University and Columbia University offer robotics concentrations. Instead of providing a sequence of robotic courses, other institutions choose to offer one or two courses, aiming to prepare students with the basic knowledge and skills to design and program robots. Core courses offered by various ME, EE, CE, CS, engineering schools, robotic institutes usually address:

- *Autonomous Mobile Robot:* CPE 416: Autonomous Mobile Robotics by the CE Dept. at Cal Poly; CPE 521: Introduction to Autonomous Robots by the Schaefer School of Engineering & Science at Stevens Institute of Technology; CMSC 479/679: Introduction to Robotics by the Dept. of Computer Science and Electrical Engineering at University of Maryland Baltimore County; EECS 568: Mobile Robotics: Methods & Algorithms by the University of Michigan Robotics Institute
- *Robotic Manipulator:* ME 598: Introduction to Robotics by the ME Dept. at Stevens Institute of Technology; ECE 470/AE 482/ME 445: Introduction to Robotics by the ECE Dept. at UIUC; CS223A: Introduction to Robotics by Stanford Engineering Everywhere at Stanford University
- *AI (Artificial Intelligence) Robots:* CS 4981R: AI for Robot Manipulation by the CS Dept. at UIUC; CSC 499: Introduction to Robotics by the Dept. of ECE and CS at Jackson State University; CS 7638: Artificial Intelligence for Robotics by the CS Dept. at Georgia Tech
- *Combination of Topics in Autonomous Mobile Robot and Robotic Manipulator:* EE I5500: Introduction to Robotics by the EE Dept. at City College of New York (CCNY); ME 598 Introduction to Robotics by the ME Dept. at Stevens Institute of Technology; MEAM 520 Introduction to Robotics by the Dept. of Mechanical Engineering and Applied Mechanics at University of Pennsylvania (UPenn)

Clearly, different departments choose to teach topics from their own expertise. For instance, the ME Dept. would focus on mechanical design; the EE, CE, or ECE departments typically cover sensing, dynamics, motion control; and the CS Dept. would focus on high-level algorithms such as path planning and computer vision. Since the field of robotics moves quickly and encompasses a wide range of disciplines, the robotics education must be adaptive and incorporate a multidisciplinary approach. The key is to provide education in the fundamentals, while maintaining strong connections to current research [10].

The research question addressed in this paper is on designing an introductory robotic course in an undergraduate curriculum from an EE, CE, or ECE perspective that is fundamental, multidisciplinary, and adaptive so that it can reflect the fast-developing characteristics of the robotic field and culture undergraduate research activities. Specifically:

A. *Fundamental:* The course will address fundamental subjects pertaining to robotics. It can be used as either a sole course introducing students to robotics or the first course in a sequence of courses.

B. *Multidisciplinary:* The course needs to provide students with a relatively “complete” picture of typical topics in robotics, together with the commonly-used mathematical tools, theories, and methods. That is, the course needs to present the multidisciplinary aspects of robotics, equipping students with basic knowledge in several closely-related disciplines (EE, CE, ME, and CS).

C. *Adaptive:* The field of robotics changes rapidly each year. Due to this fast-developing feature, certain subjects that were once taught at the graduate level can be brought into the undergraduate curriculum. The course needs to be able to include more-advanced and/or graduate-level topics.

D. *Hardware Allowing Extension or Integration with Other Devices:* Physical robots are widely adopted by educators to use in the classroom [17, 18, 19, 20, 21, 22]. Recently, educational robots have become more affordable than in the past. The adopted hardware (robotic platform) needs to allow further extension and/or integration with other devices so that the physical robots can be used for more than one dedicated application scenario.

E. *Promoting & Incorporating Undergraduate Research:* In addition to the four primary factors mentioned above, another aspect that we would address is the potential promotion and incorporation of undergraduate research [11, 23]. Students taking this course are likely in their junior or senior years. It is time for them to be exposed to projects and applications of research flavors.

This paper reflects 10-year development and teaching of two robotic courses across two institutions. The course content, teaching approaches, hardware & software solutions, and the mechanism of incorporating advanced topics into the courses are presented in details. The first course is “ELMC 2080: Introduction to Robotic Systems”, offered by the ECE Dept. at Wentworth Institute of Technology (WIT) as an elective to junior students in various engineering majors. The second course is “CET 4952: Robotics Technology”, offered by the CET Dept. at New York City College of Technology (City Tech) as a technical elective to its senior students. Both courses:

- Have lecture and lab sessions each week.
- Cover topics in two areas: Autonomous Mobile Robots and Robotic Manipulator.
- Aim to expose students to fundamental concepts, theories and algorithms in robotics, as well as to strengthen students’ hands-on skills. The fundamental subjects include navigation, map building, path planning, sensing and perception, image processing in Autonomous Mobile Robot and homogeneous transformation, forward & inverse kinematics, trajectory generation, Jacobian and singularity, independent joint control in Robotic Manipulator.

Regarding course content, we decided to include topics in both Autonomous Mobile Robot and Robotic Manipulator (shown in Table 1), since these topics are fundamental to students in EE, CE, and ECE majors. Covering topics in both areas help to serve students of different backgrounds and interests, as well as bringing the multidisciplinary feature. Courses are structured to have both lecture and lab sessions. During lectures, traditional instructional style is used where the instructor explains materials and answers students’ questions. In the lab sessions, students are provided with hardware and are asked to complete three projects over one semester. Project-based learning [24, 25, 26] is adopted in the first two projects. The final project is usually open-ended, exposing students to more advanced tasks of research flavors.

In terms of hardware, we started by using LEGO Mindstorms NXTs (http://www.lego.com) [27] and then switched to the VEX Robotic Kit (https://www.vexrobotics.com/) [28, 29]. For software, RobotC (http://www.robotc.net) is used which provides a true C programming environment. The VEX kit includes many mechanical parts, electronics components, motors, and sensors, yielding versatile robots. For example, an autonomous mobile base can be built to implement algorithms on Autonomous Mobile Robot. By further adding a simple robotic arm, algorithms on Robotic Manipulator can be tested.

In addition, the two Universal Asynchronous Receiver-Transmitter (UART) ports on the VEX micro-controller (Cortex) allow integration with other components and devices. Specifically, real-time onboard image processing was obtained by integrating Cortex with Raspberry PI plus its camera module [Fig. 1(a)] [30]. The resulting vision-enhanced VEX robot can be used to implement vision-based control tasks such as visual servoing and visual tracking [31]. Another extension was to achieve wireless inter-robot communication by integrating Cortex with XBee module [Fig. 1(b)] [32], yielding a robotic network as shown in Fig. 1(c). This VEX robotic network can be used to implement coordinated control tasks, such as rendezvous. Using the enhanced VEX robots with improved capabilities, more advanced control algorithms can be exposed to undergraduate students in the classroom setting.

The paper is organized as follows. Section II summarizes the projects used in the robotic course, ELMC 2080 at WIT. Section III describes the course content of the robotic course, CET 4952 at City Tech. The three projects currently used in CET 4952 are given in Sec. IV. Section V presents assessment of course learning outcomes via in-class exams, surveys of students’ feedback, and Student Evaluation of Teaching (SET). These direct and indirect assessment results together confirmed that the developed course materials and teaching methodology are effective in teaching the introductory robotic course. Section VI summarizes the paper and discusses directions for future improvement.

Undergraduate Robotic Course at WIT

The work was done when the author was with Wentworth Institute of Technology (five offerings from fall 2009 to spring 2015). Since fall 2009, the ECE department at WIT offers an elective course (ELMC 2080: Introduction to Robotic Systems) to junior students majoring in EE, CE, and Electromechanical Engineering. This course has a 1-hour lecture session and two 2-hour lab sessions each week. Lecture topics start from Autonomous Mobile Robots and transit to Robotic Manipulator. Homework assignments are given weekly, pertaining to the lecture topic of the week. Students implement algorithms on their robots during lab sessions.

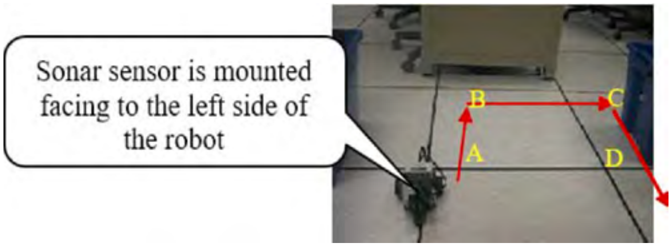
Upon selection of the robotic platform, we are in favor of small, portable, yet powerful robotic kits that allow

(a) Integration with Raspberry PI & Camera

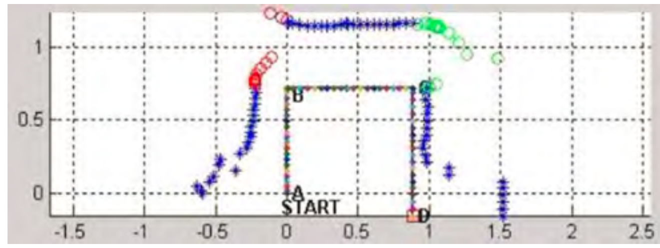
(b) Integration with XBee Module

(c) Robotic Network Built using XBee-Integrated VEX Robots

Figure 1. Enhanced VEX robots.



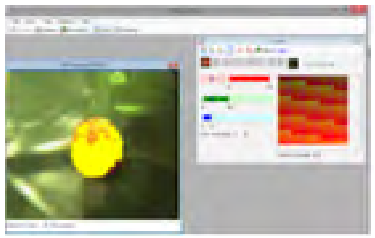
(a) Experimental Setup



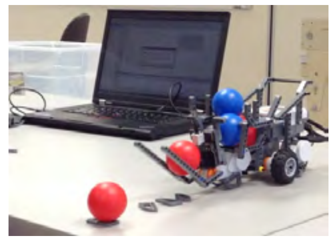
(b) Mapping of the Robot's Surroundings

Figure 2. Map building using a sonar range sensor.

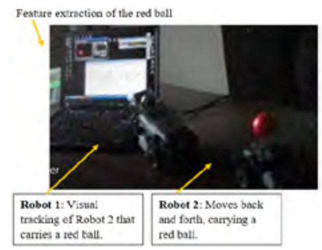
(a) NXTCam



(b) NXTView



(c) Picking Up Balls



(d) Visual Tracking

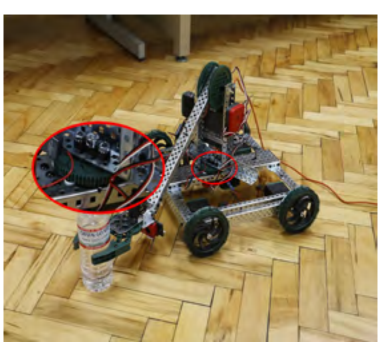
Figure 3. Vision-based control implemented on LEGO NXT.

extensions. At the beginning, the LEGO Mindstorms NXTs were used. After four semesters, the VEX robotic kits were added. Software-wise, we started by using ROBOLAB [33], which is a LabVIEW-based graphic programming language. Later, RobotC was used, which is compatible with both NXT and VEX. Two projects were implemented on NXT and the third was on VEX. The NXT robots, which are easy to use, facilitated a quick start. Students could focus on implementation of algorithms right away.

The first project is illustrated in Fig. 2. The robot builds a map of its surroundings using a sonar range sensor. When the robot goes through points $A \rightarrow B \rightarrow C \rightarrow D$, positions of the objects detected by the sonar are computed and stored. These positions are plotted offline using MATLAB. It can be seen that the map represents the robot's surroundings fairly well. This project successfully guides students to command the robot to translate, rotate, navigate through a given list of points, use the sonar sensor to build a map, and use MATLAB for offline plotting.

The second project exposes students to vision-based control. We used the NXTCam [34] that is compatible with NXTs [Fig. 3(a)]. The NXTCam needs to be "trained" beforehand using a software called NXTCamView [35], where the lower and upper thresholds of red, green, and blue colors are adjusted until the object is properly extracted on the image plane [Fig. 3(b)]. These color thresholds are then uploaded to the NXTCam to be used with NXTs. Samples of students' work are shown in Fig. 3(c) and (d). In (c), students used the NXTCam to align the robot toward several colored balls to pick them up one at a time. In (d), one NXT robot was controlled to follow another NXT robot carrying a red ball.

The third project focuses on the robotic arm built using the VEX kit. The task is to command the robot's end-effector to pick up an object (or several objects). Students were allowed to define their own scenarios and control schemes. For example, one group assumed that the location of the target was known. They designed a robot whose "neck" can be rotated with respect to the base. Instead of rotating the mobile base, the "neck" was rotated, sending the end-effector to approach the target [Fig. 4(a)]. Another group of students focused on mechanical design of a powerful end-effector that can pick up several balls at the same time [Fig. 4(b)]. The robot rotated in place to find objects in its neighborhood using a sonar range sensor. Once aligned to the objects reasonably well, the robot simply moved forward to pick them up. As can be seen, different groups had different ideas. This project provided an opportunity for students to come up with innovative designs, to be independent and creative.



(a) With a Rotating "Neck"

(b) Powerful End-Effector

Figure 4. Samples of students' projects at WIT.

This section describes the teaching experience of a junior-level introductory robotic course that serves as an elective for students in several engineering majors. Hardware-wise, both NXT and VEX were used as the robotic platforms. For software, we feel that RobotC was powerful enough to implement algorithms at the college level. Since RobotC supports both NXT and VEX in a similar manner, students didn't spend extra effort transitioning between hardware platforms (i.e., from NXT to VEX). Starting with NXTs that are relatively smaller, two students formed a group, allowing each member to have adequate access to the robot. Having obtained basic software and programming skills, students were given the VEX kits, being exposed to more realistic robots. This time we suggested the students to form a group of three members, with one being "good" in mathematics, one in programming, and the other in hardware.

Undergraduate Robotic Course at New York City College of Technology

This section describes the development, evolution, and teaching of "CET 4952: Robotics Technology" during six offerings from spring 2017 to fall 2019. The course is offered by the CET Dept at City Tech as a technical elective to its senior students. It is offered twice a year in both spring and fall semesters. As an introductory course to robotics, it also covers topics in both Autonomous Mobile Robots and Robotic Manipulator. Several books are selected as references, including, "Autonomous Mobile Robots" [36], "Robot Modeling and Control" [37], and "Robotics, Vision, and Control" [38]. This course is structured to have a 2.5-hour lecture session and a 2.5-hour lab session each week. In the lab session, students are provided with physical robotics to implement algorithms discussed in lectures. Project-based learning is adopted. Students, who work in groups, need to perform three projects in one semester. Details of lesson plan, course learning outcomes, and projects are given next.

A. Course Content

Typical fall and spring semesters at City Tech have fifteen weeks. Table 1 shows the course content in the form of a fifteen-week lesson plan. Different from the robotic course (ELMC 2080) offered at WIT to junior students, this course is targeted toward senior students. Comparing to ELMC 2080, the lecture time of CET 4952 is longer (2.5 hours in CET 4952 vs. 1 hour in ELMC 2080), the total duration of lab hours is less (2.5 hours in CET 4952 vs. 4 hours in ELMC 2080), and the students are more matured (seniors in CET 4952 vs. juniors in ELMC 2080). Longer lecture sessions allow discussion of more course materials. The shortened lab hours are accommodated by more matured students who were observed to do well in managing their projects.

B. Course Learning Outcomes

Upon completion of the course, students are expected to be able to:

1. perform path planning for a mobile robot in a structured environment.
2. command the robot to follow a trajectory given by a list of waypoints.
3. build a simple map using the onboard range sensors on a mobile robot.
4. demonstrate knowledge & understanding of fundamental image processing functions and the camera's perspective projection model.
5. demonstrate knowledge of the relationship between mechanical structures of industrial robots and their operational workspace characteristics.
6. demonstrate an ability to apply spatial transformation to obtain forward kinematics of robot manipulators.
7. demonstrate an ability to solve inverse kinematics of simple robot manipulators.
8. demonstrate an ability to generate joint trajectory for motion planning.
9. demonstrate an ability to obtain the Jacobian matrix and use it to identify singularities.

C. Three Projects used in Lab Sessions

In addition to improving students' hands-on skills, the objectives of the lab/project activities are to aid in their study and understanding of lecture materials, motivate students to learn more about robotics and the general STEM fields, and to enhance interdisciplinary and critical/creative thinking skills. Project-based learning, which provides active, collaborative and problem-based learning style, has been adopted in the lab sessions [24, 25, 39]. Typically, three students form a group and work collaboratively to solve problems together. Three projects of increasing complexities were assigned. Project 1 prepares students to establish basic understanding and programming experience of autonomous mobile robots. Students will then acquire more solid programming and integration skills in Project 2, focusing on a robotic arm. Project 3 exposes students to more advanced software design, algorithm implementation, and system integration. Step by step, students will acquire the knowledge, skills, and experience of designing & implementing algorithms for robotic control applications. The three projects are:

- Project 1: Basic Motion Control of an Autonomous Mobile Robot in 2D Space. Typical steps include: a) construction of VEX robot; b) translation: command the robot to move forward to a specified distance; c) rotation: command the robot to rotate to a given angle; d) waypoints navigation: command the robot to navigate through a list of waypoints; and e) map building: obtain a map of the robot's surroundings using sonar range sensors as the robot moves around.
- Project 2: Inverse Kinematics of the VEX Robotic Arm. This project aims at controlling the robot's end-effector to specified positions in the 3D space. More details are given in Sec. IV-A.
- Project 3 (Final Project): The purpose is to introduce more advanced topics and robotic applications. Three candidate options are given, among which students can choose to do one.
  - Visual Servoing (Sec. IV-B): The robotic platform is a vision-enhanced VEX robot that is obtained by integrating VEX with Raspberry PI. The control objective is to orient the robot to a target, keeping a certain distance in between.
  - Coordinated Control (Sec. IV-C): The robotic platform is a VEX robotic network consisting of 2~3 XBee-integrated VEX robots. The control objective is to achieve rendezvous, commanding all robots to reach the same location from different initial positions.
  - Students Proposing Their Own Projects: The purpose is to allow students to explore on their own. Samples of students' projects are to be described in Sec. IV-D.

Week	Lecture (2.5 Hours per Week)	Project (2.5 Hours per Week)
1	Introduction	Project 1: • Construction of an autonomous mobile robot • Translation • Rotation • Navigation • Map Building
2	Map Building; Path Planning; Localization	
3	Sensors	
4	Introduction to Image Processing	
5	Camera Modeling	
6	In-Class Exam #1	
7	Homogeneous Transformation	Project 2: • Construction of the robot with an arm • Modeling and Analysis • MATLAB Simulation • Implementation on the robot
8	Parameterization of Rotation Matrix	
9	Forward and Inverse Kinematics (1)	
10	Forward and Inverse Kinematics (2)	
11	Trajectory Generation	
12	Jacobian Matrix and Singularities	Project 3: Students can choose one from several options provided by the instructor or propose to do a project of their own. Each group will demonstrate their project to the class in the last day of lab session.
13	Independent Joint Control	
14	Review	
15	In-Class Exam #2	

Table 1. Course Content

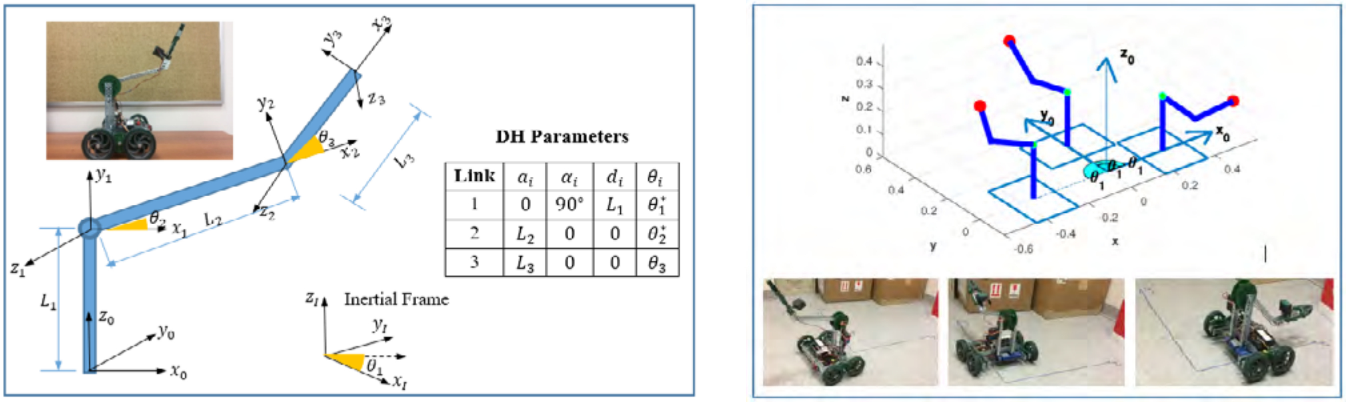
Projects Implemented On Vex Robots

This section describes three projects that were implemented on VEX or VEX-based robots for teaching robotics in an undergraduate robotic course. These projects can serve as initial setup or prototype to involve students in undergraduate research. In addition to improving students' hands-on skills, the objectives of the lab/project activities are to aid in their study and understanding of lecture materials, motivate students to learn more about robotics and the general STEM fields, and to enhance interdisciplinary and critical/creative thinking skills.

A. Control of a VEX Robotic Arm

This section describes how a VEX robot can be used as a platform to apply the knowledge that students learned

$$P_1^I = \begin{bmatrix} 0.6 \\ 0 \\ 0.1 \end{bmatrix}, \quad P_2^I = \begin{bmatrix} 0 \\ 0.6 \\ 0.3 \end{bmatrix}, \quad P_3^I = \begin{bmatrix} -0.6 \\ 0 \\ 0.5 \end{bmatrix}.$$



(a) Modeling (b) Experiment

Figure 5. Modeling and control of a VEX robotic arm.

on Robotic Manipulator. The objective of the project is to control the robot's end-effector to go through a sequence of specified "via-points", whose coordinates are given referring to an inertial frame. This project, typically running five weeks long, starts by modeling a VEX robotic arm and obtaining both forward and inverse kinematics. Simulation is performed to verify the correctness of the derived inverse kinematics. After that, experiments are conducted on the VEX robotic arm. Upon successful completion of the project, students will go through several important steps in solving an engineering problem, i.e., modeling, analysis, simulation, and experiment.

Details of this project are given in [40]. Figure 5(a) shows the modeling, including selection of reference frames and Denavit-Hartenberg (DH) table. In the experiment as shown in Fig. 5(b), the robot's end-effector successfully went through the following three points as specified:

B. Visual Servoing

Vision-based control was introduced to the students in fall 2018, using the vision-enhanced VEX robot in Fig. 1(a). It is worth mentioning that the resulting vision-enhanced VEX robotic system is different from that of the LEGO NXT equipped with a NXTCam. For the LEGO NXT with NXTCam, feature extraction of the target on the image plane uses pre-trained thresholds obtained in a separate software, NXTCamView. Students do not actually perform image processing on their own, at least not at the programming/code level. They simply use a computer vision product offered by others. Instead, the vision-enhanced VEX robot provides access to the full open-source computer vision library, OpenCV (https://opencv.org). Students can actually program computer vision tasks on their own, without being restricted by functionalities provided by a third-party software.

A visual servoing task was implemented on the vision-enhanced VEX robot. The control objective is to command the robot to orient to a target while keeping certain distance away from it. As a simple start, we assume that the target is stationary, the pattern of the target is known (so that we can look for this pattern in the image plane to find the target), some size information of the target is available, and the PI camera is calibrated beforehand. Specifically, let L denote the known size of the target. For example, if the target is a circle, can be selected to be the circle's radius or diameter. Let $L_{in-pixels}$ denote the corresponding length in pixels found on the image plane. Then, the relative distance between the target and the camera, i.e., the depth, can be computed as [31]:

$$Z_c \approx \frac{\alpha L}{L_{in-pixels}} \tag{1}$$

where α is one of the camera's intrinsic parameters calibrated in advance. When a desired relative distance (Z_c) is specified, the desired length on the image plane can be computed and used to control the robot.

The robot is controlled to first rotate to search the target until the target gets close to the image center horizontally. The robot then moves toward it, with the Raspberry PI constantly checking if the desired length in pixels has been reached. If so, Raspberry PI sends a message to the robot to stop its motion. Information exchange between the VEX Cortex and the Raspberry PI occurs in one direction, i.e., from Raspberry PI to Cortex. This information includes a) 'R' standing for rotation to the right of the robot; b) 'L' for rotation to its left; c) 'S' for moving straight; and d) 'T' for termination of the task. In the experimental results shown in Fig. 6, the figures on the top show the motion of the robot and the figures on the bottom present the corresponding image processing results.

For simplicity, the target is selected to be a black circle in a clean background. The robot starts from a position far away from the target, facing slightly to its right. To orient to the target, the robot rotates to its left until the target appears close to the image center. The robot then moves straight toward the target until the desired length in pixels has been reached. Correspondingly on the image plane, the target first moves to the image center, and then appears

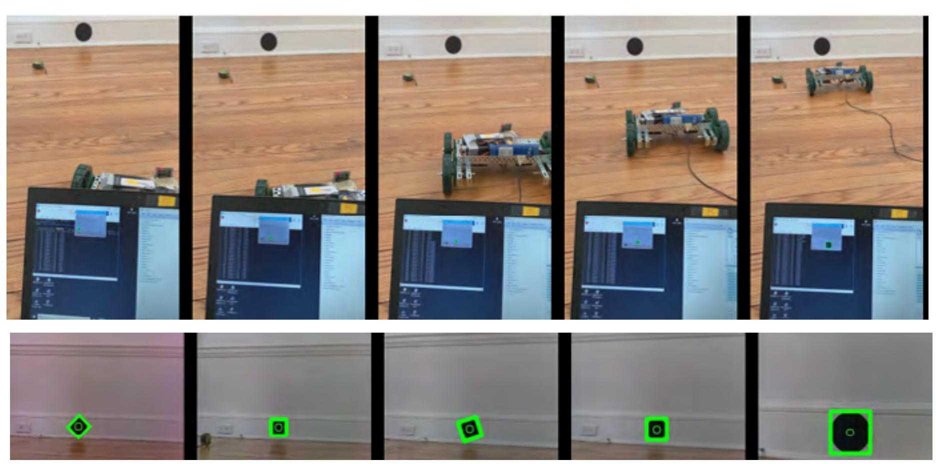


Fig. 6. Visual servoing of a vision-enhanced VEX robot.

bigger and bigger as the robot moves closer to the target.

Currently, the visual servoing project was achieved by sending information from the PI to the Cortex. In the future, we will investigate control of the VEX mobile base (motors with integrated encoders) from the PI directly.

C. Coordinated Control

Coordinated control was demonstrated to the students in spring 2019, using a VEX robotic network consisting of two to three XBee-integrated VEX robots. The XBee modules allow the robots to communicate with each other wirelessly [Fig. 1(b) and 1(c)]. With the added capability of wireless inter-robot communication, the resulting VEX robotic network can be used to implement coordinated control algorithms.

A simple coordinated control task, rendezvous [41, 42], was achieved on up to three XBee-integrated VEX robots [43]. Rendezvous refers to the task of commanding a group of robots to reach the same location from different initial positions. The following discrete-time rendezvous controller was implemented:

$$\Delta x_i(k) = x_i(k+1) - x_i(k) = \sum_{j \in N_i} \kappa_i \left(x_j(k) - x_i(k) \right) \quad (2)$$

where $x_i(k)$ and $x_i(k+1)$ denote the positions of the i^{th} robot at time instances k and $k+1$. The parameter κi is the controller gain for the i^{th} robot. N_i denotes the neighborhood of the i^{th} robot, which currently includes the rest of the robots corresponding to an all-to-all communication topology [44]. Communication protocols for information exchange of each robot's position was designed in-house.

One set of experimental results is shown in Fig. 7, where three robots are commanded to reach one location from different initial positions. The trajectories of the three robots are plotted in different colors (purple, blue, and black) in the top figure. The initial orientations of the three robots are indicated by the three black arrows. Snapshots of the robots' motion are shown in Fig. 7(b). It can be seen that all robots were controlled to arrive at the same location successfully. Coordinated control is a more advanced control topic. Using the XBee-integrated VEX robots, students can be exposed to research topics as such.

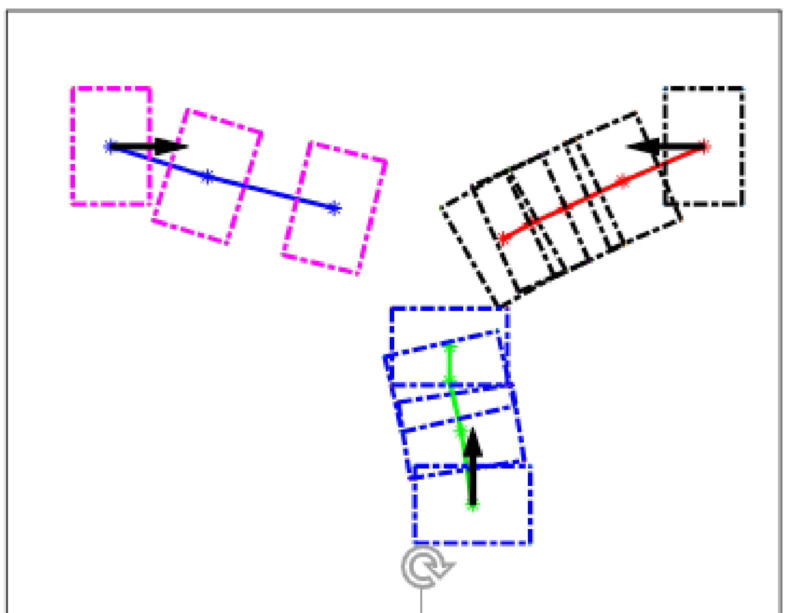
D. Samples of Students' Work

This section presents samples of students' projects collected between spring 2017 and fall 2019. Figure 8(a) shows the setup for path planning of an autonomous mobile robot (Project 1). The tiles on the floor were used as the grid map. The robot was asked to go from an initial position to reach a specified goal location, detecting objects as it traveled on its way. Since detailed instructions and help were given to the students, this project usually went very well. Evaluation of the project is based on both the robot's behavior and accuracy. Specifically, 4 (out of 10) points will be given if the robot finds a clear (obstacle-free) path from its current position to the specified goal position; 4 points if the robot follows the path reasonably well; 2 points if the robot arrives at the goal location (as long as any part of the robot is inside the goal grid); and 2 points if the trajectory of the robot, along with objects detected by its onboard sonar sensor, is properly plotted using MATLAB offline. Algorithms needed by this project were discussed in lectures. Students were able to understand them properly. Some students had difficulty in writing C codes to implement these algorithms. The instructor helped by reviewing C programming (loop, 1D & 2D arrays), suggesting the outline of the program, and by specifying functionalities of the sub-functions.

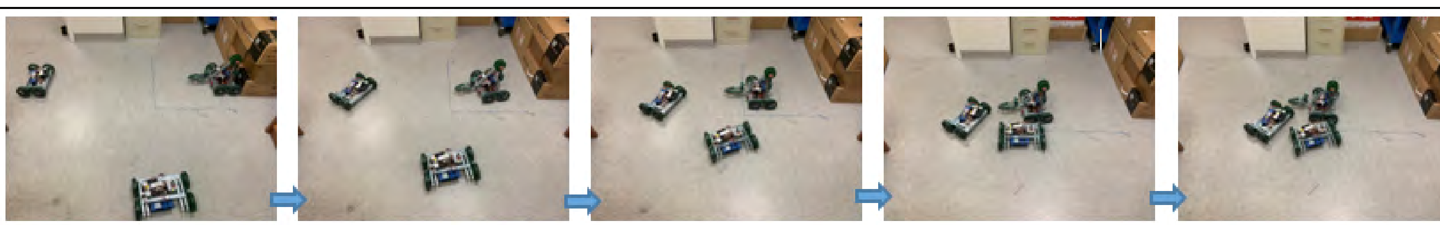
Figure 8 (b) and (c) illustrate Project 2 on controlling the robotic arm's end-effector to reach a specified location in 3D. This project requires study of the robot's forward & inverse kinematics, and essentially obtaining the robot's DH table and the parameters needed (distance between the "shoulder" and the mobile base, length of the arm, and the fixed angle between the arm and the end-effector). Notice that when obtaining these measurements, errors can be introduced. Another source of error comes from the accumulated errors in the wheels' integrated encoders, which were used to determine how far the robot has traveled. Evaluation of this project is based on if the robot's end-effector can be controlled to reach the proximity of the specified location. If the relative distances in *x*,*y*, and *z*- directions are within roughly 2~3 cm, full credits are given. With the preparation of programming skills in Project 1, students became more independent when doing this project. A common issue observed is in selection of the "right" set of solutions (from the two sets of solutions) for the inverse kinematic problem. Some groups just randomly selected/implemented one set. The robot went beyond and then tried to lift its arm back. It was until this point that students realized that they needed to use the other set of solutions.

Figure 8 (d) shows an omnidirectional robot, serving as the final project (Project 3). This robot can be controlled to translate and rotate at the same time. This group built the robot all by themselves. The instructor didn't provide any help.

Figure 8 (e) shows a robot built from scratch, serving as the final project. This group tried to duplicate/mimic the VEX robot with much cheaper components. They did



(a) Trajectories of the Three Robots



(b) Snapshots of Robot's Motion

Figure 7: Coordinated control of a VEX robotic network.

everything on their own (mechanical design, 3D modeling, 3D printing, selection of electronics, motors, sensors) and programmed the robot to reproduce what was done in Projects 1 and 2.

Figure 8 (f) shows one groups' work on integration of Internet of Things (IoT) with the VEX mobile base via Raspberry PI. This project also served as the final project, without any help from the instructor. Students demonstrated that the robot can be controlled to move around (forward, backward, left and right turns) from a computer that is on the same network as the Raspberry PI.

Figure 8 (g) shows another group's work on image processing and depth recovery implemented on MATLAB. Different from all above-mentioned projects that involve both a physical robot and software, this project involves only a USB camera connected to the computer. The students used MATALB's Image Acquisition Toolbox to capture videos in real-time, detected the radius of a circle (whose radius is known beforehand), calibrated the camera, and computed the relative distance between the camera and the target (i.e., the circle). The instructor provided help in using several functions in MATLAB's Image Processing Toolbox.

Figure 8 (h) shows students' work on the visual servoing project. The control objective is to command the robot to follow the black circle, i.e., the target. A prototype of the vision-enhanced VEX robot was provided to the students, with some sample codes in image processing and UART communication (between the Cortex and the Raspberry PI). After getting familiar with the entire system, the students spent a great amount of time working on feature extraction of the target. The typical issue encountered was to extract the target correctly/properly from the noisy background on the image plane. Students tried fine-tuning of the color thresholds of a colored object, as well as extracting the circle out using intensity. In both cases, it was still hard to extract the target from the background with many objects. Eventually, the students placed the robot to face a "clean" background (i.e., the wall) and demonstrated successful visual servoing. Though image processing is quite a challenging task, students got a clear picture of vision-based control.

Students' final projects range from doing purely software [MATLAB image processing in Fig. 8 (g)], mainly hardware [omnidirectional robot in (d)], mainly software [IoT in (f) and visual servoing in (h)], to design of a complete robotic system [in (e)]. Different expertise was observed among different students and groups, making them select projects of different focus. For instance, students who selected the visual servoing project had used Raspberry PI before; students doing an IoT project had taken (or were taking) an IoT course; and the group doing the project in Fig. 8(e) was working with another processor on undergraduate research.

It was also observed that groups tend to select different projects for the final project. With typically seven groups in one semester, there were usually four different topics. All students were thus exposed to different projects in the classroom setting. Though students focused on their own project most of the time, they also walked around, talked to other groups, and were aware of what other groups were trying to achieve. The end-of-semester demonstration gave students opportunities to ask questions and provide suggestions/feedback to other groups' projects.

Survey and Assessment Results

Assessment of students' learning performance and course content provides feedback on the effectiveness of course materials, lesson plan, and the general teaching philosophy. Thus, assessment is considered as an important component and was performed every semester since spring 2017. Both direct and indirect assessments are used [45, 46]. Direct assessment tools include the midterm exam and the final exam, which are in-class, closed-book, and closed-computer. These assessments are mainly used for evaluating students' learning outcomes. Under indirect assessment, surveys of students' opinions about the course content and projects, together with end-of-the-semester Student Evaluation of Teaching (SETs), are used. These surveys and SETs are mainly used to evaluate the course itself.

A. Assessment of Course Learning Outcomes

From spring 2017 to fall 2019, the midterm exam and the final exam were used to evaluate course learning outcomes 1~4 and 5~9, respectively. Both exams were in-class, closed-book, closed-computer. They provided summative assessment of students' learning and knowledge [47]. Notice that course learning outcomes (1~4) and (5~9) are regarding students' knowledge on autonomous mobile robots and robotic manipulators, respectively. Table 2 shows the percentage of students who perform at the "Proficient and/or Satisfactory" level (with an exam score 70 above out of 100).

Setting as the target for being "Proficient and/or Satisfactory", it can be seen that course learning outcomes (1~9) were obtained except in spring 2017 for outcomes (5~9). The reason was mainly due to students' versatile math background in Linear Algebra, which is intensively used in the study of Robotic Manipulator. After identifying this weak area, we started reviewing linear algebra whenever needed in the course. Assessment results were improved since then and stabilized above the target value of 70%.

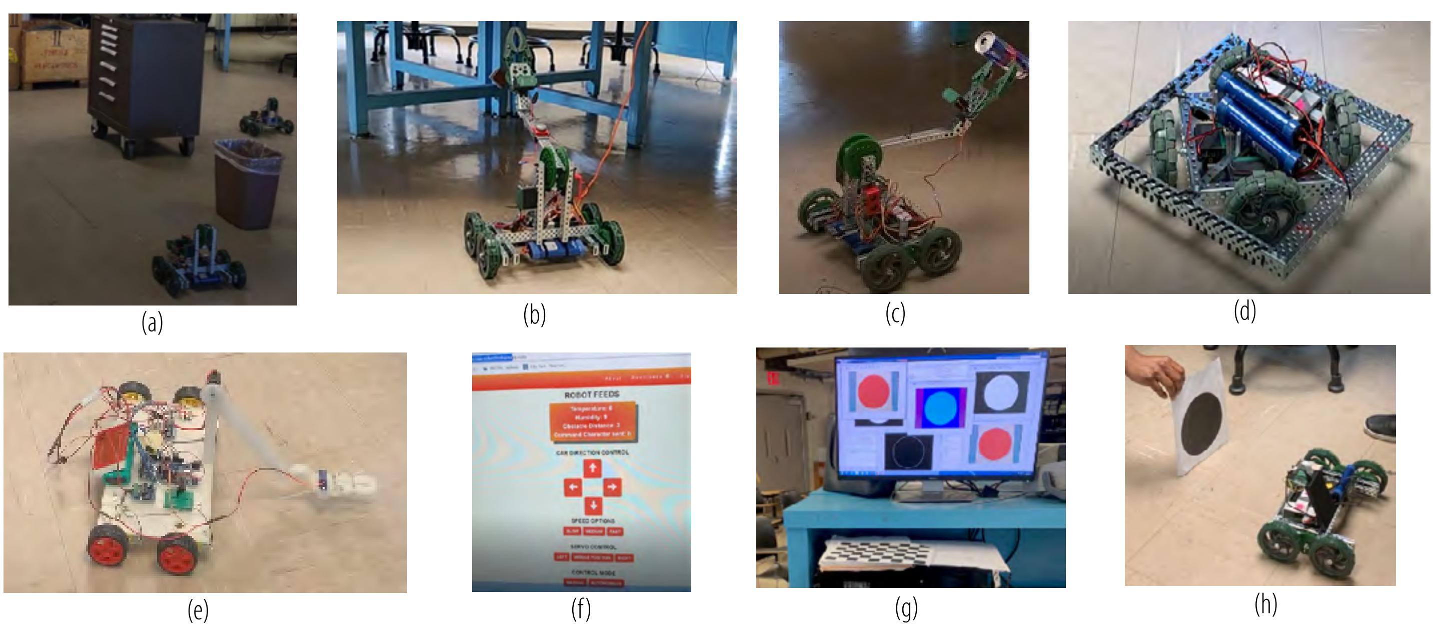


Figure 8. Sample of students' work at City Tech.

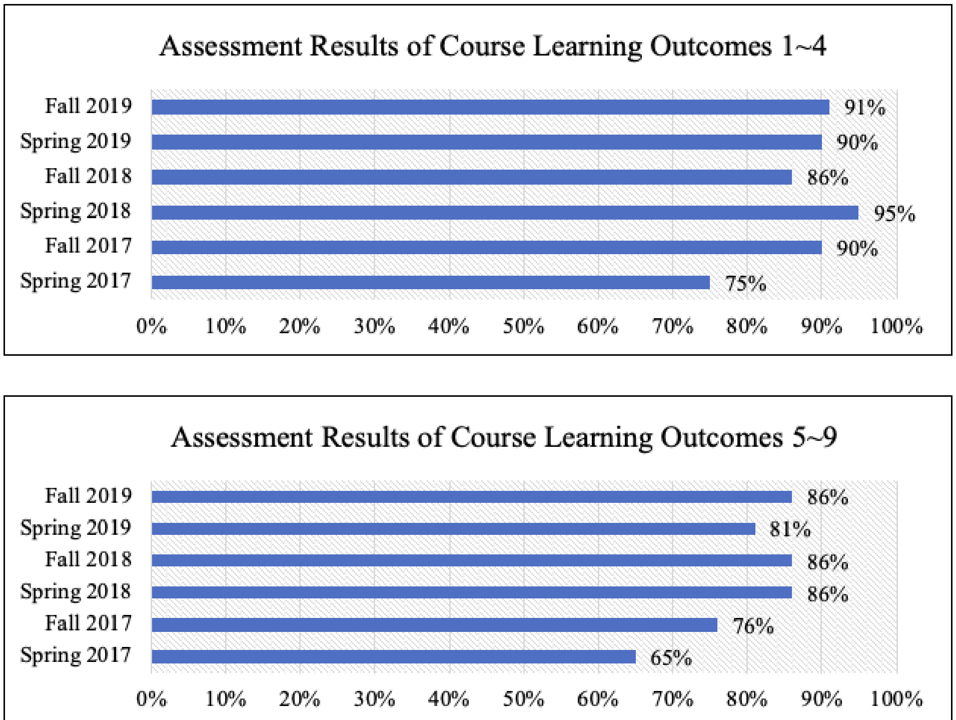


Table 2. Evaluation of Course Learning Outcomes

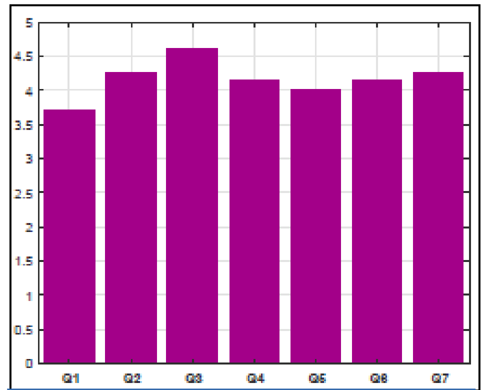


Figure 9: Survey results conducted in spring 2018 with 20 participating students, on the recently-added project of "control of a VEX robotic arm".

B. Survey Conducted in Spring 2018

Projects are major components of robotic courses, since they provide students with opportunities to work on physical robots and obtain hands-on experience. For continuous improvement, we added new projects into this course to provide students with more variety and options. We started by having two projects in spring 2017 (one on motion control of a LEGO robot and the other on simulation of a robotic arm using Peter Corke's MATLAB Robotic Toolbox [48]). We added control of a VEX robotic arm (as described in Sec. IV-A) in spring 2018, introduced vision-based control (Sec. IV-B) in fall 2018, and added coordinated control (Sec. IV-C) in spring 2019. Along the line of developing new projects, surveys were conducted to collect students' feedback regarding if the newly-added projects help to strengthen their understanding of robotic algorithms, as well as relate theories to real-life applications.

The project on "Control of a VEX robotic arm" (Sec. IV-A) was introduced to the robotic course in spring 2018. Since then, it serves as a mandatory project focusing on forward & inverse kinematics and trajectory generation of a simple robotic manipulator. To study the effectiveness of this project and the overall lesson plan, a survey was conducted in spring 2018, with the following questions:

1. The lecture motivates me toward Autonomous Mobile Robots and Robotic Manipulators.
2. The lecture materials help me to understand subjects of Autonomous Mobile Robots and Robotic Manipulator.
3. The project is closely relevant to the topics discussed in lectures.
4. The project helps me to learn science and engineering principles.
5. The project helps me to enhance interdisciplinary skills.
6. The project helps to enhance my capability on critical thinking.
7. Overall, the project improves my learning experience.

Among these questions, Questions 1 and 2 are regarding the lesson plan and lectures, and the rest of the questions are regarding the newly-added project. All questions have five choices: *Strongly Agree* (5), *Agree* (4), *Somewhat Agree* (3), *Disagree* (2), and *Strongly Disagree* (1). Using the numerical values (1~5) to represent responses of the 20 participating students, students' anonymous responses of these questions are shown in Fig. 9. Using a threshold of , which corresponds to , the assessment results demonstrate the effectiveness of this project and the overall lesson plan.

C. Survey Conducted in Spring 2019

In spring 2019, the projects on vision-based control (Sec. IV-B) and coordinated control (Sec. IV-C) were brought into the robotic course. These two projects serve as options for the final project, focusing on more advanced robotic applications. A survey was conducted in spring 2019, to collect students' feedback and opinions about these two projects and the general arrangement of having a) three projects in one semester and b) allowing students to do different projects in the third project. Specifically, the survey questions are:

1. The course, in its current shape, provides discussion of fundamental concepts in both Autonomous Mobile Robot and Robotic Manipulator.
2. The course motivates me to learn more about robotics science, theories, and algorithms.
3. The projects help me to understand the theories and algorithms discussed in class.
4. The 1st project provides me enough opportunity to work with Autonomous Mobile Robot.
5. The 2nd project provides me enough opportunity to work with Robotic Manipulator.
6. The 3rd project allows students to work on different projects. This is good and reasonable.
7. This course motivates me to explore more on construction, implementation, testing, and programming of robots.
8. Overall speaking, the course is a good resource to learn and practice my knowledge and skills in the STEM field.

Among these eight questions, Questions 1, 2 are regarding the lesson plan and lectures; Questions 3~6 are for each of the three projects and the arrangement of having three projects in one semester each targeting one particular area (autonomous mobile robot, robotic manipulator, and more advanced robotic control); and Questions 7, 8 are regarding boosting students' interest in robotics and the general STEM fields. Using the numerical values of 1~5 to represent responses of 19 participating students, the survey results are shown below in Fig. 10. Again, using a threshold of corresponding to , these results demonstrate the effectiveness of the lesson plan and the arrangement of having three projects used in the course.

Notice that the questions in the spring-2018 and spring-2019 surveys are not exactly the same. Though being slightly different, both surveys are concerned with the same three categories of questions, as shown below. In the future, surveys of more consistent questions will be conducted regularly.

Results in Figs. 9 and 10 show that students' responses confirmed the effectiveness of the lesson plan, the arrangement of having three projects, the effectiveness of each project, and the mechanism of using robotics to motivate students to know more about the general STEM

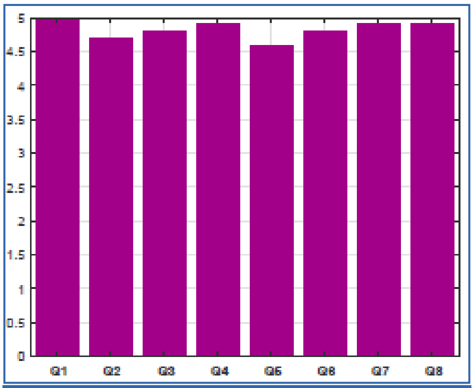


Figure 10: Survey results conducted in spring 2019 with 19 participating students, on the recently-added projects of "vision-based control" and "coordinated control".

fields. Slightly better results were obtained in spring 2019 (as compared to spring 2018), probably due to the fact that the overall lesson plan and teaching approaches have stabilized after more offerings.

D. Student Evaluation of Teaching (SET) Results

Another way of demonstrating the effectiveness of course content, projects, and teaching approaches is via the end-of-semester Student Evaluation of Teaching (SET). It is worth mentioning that researchers and educators in higher education have not reached an agreement about the validity of using SET as an evaluation approach for courses. The doubts are regarding its reliability (carelessness and inconsistency in students' answers [39]), validity (students are not yet qualified to make sound judgements [39]), and potential biases (affected by grading leniency and prior subject interest [49]). Other studies show that SET is positively related to students' perception of their own learning [50]; SET leads to improvement of faculty teaching methods and thus the quality of learning available to students [51]; and there is no adequate single indicator of effective teaching, and thus all indicators of teaching effectiveness, not just SETs, must be systematically examined before they are actually used [49].

Being aware that SET results cannot be used as the single/sole indicator for effective teaching, SET results of the past six offerings are presented in Table 3 below, as a supportive measure that needs to be examined and interpreted together with other assessment tools & results (presented earlier in Secs. V-A, V-B, and V-C) to draw an affirmative conclusion of course content and teaching effectiveness.

In fall 2017, the VEX robotic kits arrived around the middle of the semester and were used in the lab sessions right away. Students might feel sudden about this, since this was not announced at the beginning of the semester (we didn't know when the VEX kits would arrive). This explains why the evaluation for fall 2017 is slightly lower than others.

Semester	Overall Average (Out of 5)
Spring 2017	4.67
Fall 2017	4.53
Spring 2018	4.65
Fall 2018	4.72
Spring 2019	4.67
Fall 2019	4.93

Table 3. Students Evaluation of Teaching (SET) of CET 4952

Based on the direct assessment using in-class exams as shown in Sec. V-A, the survey results conducted in spring 2018 and spring 2019 as presented in Secs. V-B and V-C, along with the consistent SET results in Table 3, we think it is safe to say that the course content, designed projects, and the teaching approaches are effective in teaching the introductory undergraduate robotic course.

In addition, students in the spring 2019 class made the following suggestions:

1. Adding more simulations on lecture topics.
2. Adding obstacle avoidance.
3. Adding more implementation of sensors and actuators.
4. Adding WiFi and Internet of Things (IoT).
5. Adding Robotic Operating System (ROS).

The first comment of adding more simulations into lectures can be resolved by adding more MATLAB simulations, either MATLAB plots or MATLAB videos. The second suggestion can be handled by adding one more step in the first project. That is, after map building, the robot can plan a path based on this newly-acquired map, avoiding obstacle(s) that are detected by its onboard sensor(s). Suggestions 3~5 can be incorporated into this course by adding three more options to the final project, each corresponding to one suggestion. More specifically, one option can be exploration of several other sensors & actuators. Another option is to investigate IoT for robotics. One more option would be installing ROS on Raspberry PI. These suggestions identify directions for future development and will certainly help to improve the course.

	Spring-2018 Survey	Spring-2019 Survey
Lesson plan and lecture materials	Q2	Q1
Project(s)	Q3	Q3, Q4, Q5, Q6
Outcomes of taking the robotic course (knowing more about robotics, want to learn more about general STEM fields, improved interdisciplinary & critical/creative thinking skills)	Q1, Q4, Q5, Q6, Q7	Q2, Q7, Q8

Addressing Factors	Actions, Arrangements, Approaches
A, B	Covering topics in two areas: Autonomous Mobile Robot and Robotic Manipulator
A, B, E	Courses are structured to have lecture and lab sessions. The lab sessions give extra hours for students to master lecture topics. The lab sessions also provide opportunities for students to be exposed to real-life applications and projects of research flavors.
B, C, E	Project-based learning is adopted in lab sessions. Students are asked to complete three projects over one semester. The 1st project is on Autonomous Mobile Robot; the 2nd project is on Robotic Manipulator; and the final project exposes students to advanced open-ended robotic applications.
B, C, E	Several options (candidate topics) are provided for the final project. Students can choose to do the one that is most interesting to them.
B	The adopted hardware (VEX robotic kits) can produce versatile robotic platforms for both Autonomous Mobile Robot and Robotic Manipulator.
B, C, D, E	The VEX robots can be further integrated with other devices (such as Raspberry PI and XBee modules) to obtain onboard image processing and wireless inter-vehicle communication capabilities.
(A: fundamental) (B: multidisciplinary) (C: adaptive) (D: hardware extension) (E: promoting research)	

Table 4. Actions, Arrangements, and Approaches Addressing the Five Factors

Conclusions And Future Work

This paper summarizes the author's ten-year teaching experience of undergraduate robotic courses, one at WIT (ELMC 2080: Introduction to Robotic Systems) and the other at City Tech (CET 4952: Robotics Technology). Both courses serve as electives to expose students to fundamental concepts in the robotic science. Both courses are structured to have a lecture session and lab session(s) every week. Students use lab sessions to design and program a physical robot to reinforce their understanding of the lecture materials. Recently, enhanced VEX-based robots are used in lab sessions, allowing more advanced robotic control topics and applications to be brought into the undergraduate curriculum.

Project-based learning is adopted in the lab session for both courses. Students are asked to complete three projects over one semester. These projects include one project on Autonomous Mobile Robots (by constructing a mobile base using the VEX robotic kit), one project on Robotic Manipulator (by adding a simple robotic arm on top of the mobile base), and one project containing either research flavors (such as vision-based control and coordinated control) or showing the most recent trends in robotic applications. Combined assessments using direct assessment methods (exams) and indirect assessment tools (surveys and SETs) demonstrate the effectiveness of the designed course content, projects, and the overall teaching approaches and philosophy.

For future improvement, we plan to develop more candidate projects for the final project, including, for example: 1) exploration of more sensors & actuators; 2) ROS [12, 52]; 3) IoT robots; 4) controlling the VEX mobile base via Raspberry PI directly without using Cortex; and 5) integration of Raspberry PI with NXT bricks. Surveys of more consistent questions will also be conducted regularly, evaluating the effectiveness of the course content and lecture materials, the project(s), and the outcomes of taking the robotic course (such as knowing more about robotics, want to learn more about general STEM fields, and improved interdisciplinary & creative thinking skills).

Finally, we would like to verify that the research question posted in this paper, i.e., development of an introductory robotic course in an undergraduate curriculum from an EE, CE, or ECE perspective considering the five factor A~E as given in Sec. 1, has been properly addressed. Table 4 summarizes the actions, arrangements, and approaches taken to address these factors during the course development and evolution process. It can be seen that all five factors are adequately addressed.

References

[1] A. Minaie and R. Sanati, "An International Study of Robotics Courses in the Computer Science/ Engineering Curriculum," in *ASEE Annual Conference & Exposition*, 2006.

[2] J. Weinberg, G. Engel, K. Gu, C. Karacal, S. Smith, W. White and X. Yu, "A Multidisciplinary Model for Using Robotics in Engineering Education," in *ASEE Annual Conference & Exposition*, 2001.

[3] V. M. Jovanovic, G. McLeod, T. E. Alberts, C. Tomovic, O. Popescu, T. Batts and M. L. Sandy, "Exposing Students to STEM Careers through Hands-on Activities with Dronesand Robots," in *ASEE Annual Conference & Exposition*, 2019.

[4] M. Jou, C.-K. Huang and S.-H. Lai, "Application of Challenge Based Learning Approaches in Robotics Education," *International Journal of Technology and Engineering Education,* vol. 7, no. 2, 2010.

[5] A. Khanlari , "Effects of Educational Robots on Learning STEM and on Students' Attitude Toward STEM," in *IEEE Conference on Engineering Education*, 2013.

[6] A. L. Sala, P. Sitaram and T. Spendlove, "Stimulating an Interest in Engineering through an "Explore Engineering and Technology" Summer Camp for High School Students," in *ASEE Annual Conference & Exposition*, 2014.

[7] M. A. Gennert, N. Lotfi, J. A. Mynderse, M. Jethwani and V. Kapila, "Workshops for Building the Mechatronics and Robotics Engineering Education Community," in *ASEE Annual Conference & Exposition,* 2020.

[8] S. Gibeault, J. Lorio, J. Santillan, H. Shen and M. Tufenkjian, "Practical Application of Robotics Competition for STEM Education," in *ASEE Annual Conference & Exposition*, 2019.

[9] H. Fox, "Featuring Robotics In A Senior Design Capstone Course," in *ASEE Annual Conference & Exposition*, 2004.

[10] B. A. Maxwell and L. A. Meeden, "Integrating Robotics Research with Undergraduate Education," *IEEE Intelligent Systems and their Applications*, vol. 15, no. 6, 2000.

[11] S. Piperidis, L. Doitsidis, C. Anastasopoulos and N. Tsourveloudis, "A Low Cost Modular Robot Vehicle Design for Research and Education," in *Mediterranean Conference on Control Automation,* 2007.

[12] S. Wilkerson, J. Forsyth, C. Sperbeck, M. Jones and P. Lynn, "A Student Project using Robotic Operating System (ROS) for Undergraduate Research," in *ASEE Annual Conference and Exposition*, 2017.

[13] F. Benitti and N. Spolaor, "How Have Robots Suported STEM Teaching," in *Robotics in STEM Education,* 2017.

[14] S. Ziaeefard, N. Mahmoudian, M. Miller and M. Rastgaar, "Engaging Students in STEM Learning through Co-Robotic Hands-On Activities (Evaluation)," in *ASEE Annual Conference & Exposition*, 2016.

[15] M. McKay, S. Lowes, D. Tirthali and A. Camins, "Student Learning of STEM Concepts Using a Challenge-based Robotics Cur-riculum," in *ASEE Annual Conference & Exposition*, 2015.

[16] A. Jones and J. Straub, "Robotic Competition Teams: Assessing the Experiential Education Value of Participation," in *ASEE Annual Conference & Exposition,* 2019.

[17] C. Faria, C. Vale, T. Machado, W. Erlhagen, M. Rito, S. Monteiro and E. Bicho, "Experiential Learning of Robotics Fundamentals Based on a Case Study of Robot-Assisted Stereotactic Neurosurgery," *IEEE Transactions on Education*, vol. 59, pp. 119-128, 2016.

[18] Y. Guo, S. Zhang, A. Ritter and H. Man, "A Case Study on a Capsule Robot in the Gastrointestinal Tract to Teach Robot Programming and Navigation," *IEEE Transactions on Education,* vol. 57, pp. 112-121, 2014.

[19] H. Liu, W. Wang and R. Wang, "A Course in Simulation and Demonstration of Humanoid Robot Motion," *IEEE Transactions on Education*, vol. 54, pp. 255-262, 2011.

[20] J. McLurkin, J. Rykowski, M. John, Q. Kaseman and A. Lynch, "Using Multi-Robot Systems for Engineering Education: Teaching and Outreach with Large Numbers of an Advanced, Low-Cost Robot," *IEEE Transactions on Education*, vol. 56, no. 1, pp. 24-33, 2013.

[21] J. Tur and C. Pfeiffer, "Mobile Robot Design in Education," *IEEE Robotics Automation Magazine*, vol. 13, no. 1, pp. 69-75, 2006.

[22] J. Vega and J. Canas, "PiBot: an Open Low-Cost Robotic Platform with Camera for STEM Education," *Electronics*, 2018.

[23] B. Maxwell and L. Meeden, "Integrating Robotics Research with Undergraduate Education," *IEEE Intelligent Systems and Their Applications*, vol. 15, pp. 22-27, 2000.

[24] E. H. Fini, F. Awadallah, M. M. Parast and T. Abu-Lebdeh, "The Impact of Project-Based Learning on Improving Student Learning Outcomes of Sustainability Concepts in Transportation Engineering Courses," *European Journal of Engineering Education*, vol. 43, no. 3, 2018.

[25] A. Shekar, "Project Based Learning in Engineering Design Education: Sharing Best Practices," in *ASEE Annual Conference & Education*, Indianapolis, IN, 2014.

[26] H. Huang, J. Su and C. Lee, "A Contest-Oriented Project for Learning Intelligent Mobile Robots," *IEEE Transactions on Education*, pp. 88-97, 2013.

[27] E. Danaby, J. Brockman, A. Careberry, B. Shapiro and C. Rogers, "LEGO-Based Robotics in Higher Education: 15 Years of Student Creativity," *International Journal of Advanced Robotics Systems*, vol. 11, no. 2, 2014.

[28] Y. Liu, "From Handy Board to VEX: Evolution of a Junior Level Robotics Laboratory Course," in *ASEE Annual Conference & Exposition*, Austin, TX, 2009.

[29] R. Avanzato, "Multi-Robot Communication for Education and Research," in *ASEE Annual Conference & Exposition*, 2013.

[30] "Raspberry PI," [Online]. Available: https://www.raspberrypi.org/documentation/.

[31] L. Ma and M. Alborati, "Enhancement of a VEX robot with an onboard vision system," in *IEEE Conference on Engineering Education*, Japan, 2018.

32] "XBee Module," [Online]. Available: https://en.wikipedia.org/wiki/XBee.

[33] "ROBOLAB," [Online]. Available: http://www.legoengineering.com/platform/robolab/.

[34] "NXTCam," [Online]. Available: http://www.mindsensors.com/ev3-and-nxt/.

[35] "NXTCamView," [Online]. Available: http://nxtcamview.sourceforge.net/.

[36] R. Siegwart and I. Nourbakhsh, Autonomous Mobile Robots, MIT Press, 2004.

[37] M. Spong, S. Hutchinson and M. Vidyasagar, Robot Modeling and Control, Wiley, 2006.

[38] P. Corke, Robotics, Vision, and Control, Springer, 2011.

[39] Z. Prusak, "Course Learning Outcomes and Student Evaluations: Can Both Be Improved?," in *ASEE Annual Conference & Exposition*, 2009.

[40] L. Ma and G. Ma, "Modeling and Control of a VEX Robot," in *Hawaii International Conference on Education*, 2019.

[41] J. Cortes, S. Martinez and F. Bullo, "Robust Rendezvous for Mobile Autonomous Agents via Proximity Graphs in Arbitrary Dimensions," *IEEE Transactions on Automatic Control*, vol. 51, pp. 1289-1298, 2006.

[42] A. Sinha and D. Ghose, "Generalization of Linear Cyclic Pursuit with Application to Rendezvous of Multiple Autonomous Agents," *IEEE Transactions on Automatic Control,* vol. 51, pp. 1819-1924, 2006.

[43] L. Ma and M. Alborati, "Wireless Inter-Vehicle Communication Among VEX Robots," in *International Conference on Engineering Education*, 2019.

[44] R. Sepulchre, D. Paley and N. Leonard, "Stabilization of Planar Collection Motion: All-to-All Communication," *IEEE Transactions on Automatic Control,* vol. 52, pp. 811-824, 2007.

[45] S. B. Pidugu, M. M. Bakr, S. Midturi and G. Tebbetts, "Assessment Process Using the First Year Computer Graphics Course at University," in *ASEE Annual Conference & Exposition*, 2013.

[46] M. A. Dettman, "Developing a Sustainable Assessment Plan for EAC-ABET Accreditation," in *Eleventh LACCEI Latin American and Caribbean Conference for Engineering and Technology*, Cancun, Mexico, 2013.

[47] W. H. Guilford and B. P. Helmke, "Summative versus Formative Assessments in Teaching Physiology to Biomedical Engineering Students: A Comparison of Outcomes," in *ASEE Annual Conference & Exposition,* 2017.

[48] P. Corke, "Robotics Toolbox," [Online]. Available: https://petercorke.com/toolboxes/robotics-toolbox/.

[49] H. W. Marsh and L. A. Roche, "Making Students' Evaluations of Teaching Effectiveness Effective: The Critical Issues of Validity, Bias, and Utility," *American Psychologist,* vol. 52, no. 11, 1997.

[50] M. M. Rashid, M. Ahmed, K. Dajani, J. R. Khan and H. Bhuiyan, "Student Evaluation of Teaching Index vs. Student's Self-Evaluation: Understanding the Impact of Teaching Performance on Student Satisfaction," in *Proceedings of the Midwest Section Conference of the American Society for Engineering Education*, 2013.

[51] T. James, "Comparison of Student and Faculty Perceptions of Intent and Effectiveness of Course Evaluations in an Engineering Curriculum," in *ASEE Annual Conference & Exposition,* 2019.

[52] J. M. Canas, E. Perdices, L. Garcia-Perez and J. Fernandez-Conde, "A ROS-Based Open Tool for Intelligent Robotics Education," *Applied Sciences,* vol. 10, no. 21, 2020.

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