2023 Annual Conference & Exposition
Baltimore Convention Center, MD | June 25 - 28, 2023
The Harbor of Engineering Education for 130 Years
Paper ID #37271

Designing Learning Experiences with a Low-Cost Robotic Arm

Prof. Eric Markvicka, University of Nebraska-Lincoln

Dr. Eric Markvicka is an Assistant Professor in the Department of Mechanical and Materials Engineering at the University of Nebraska-Lincoln (UNL). There, he also holds a courtesy appointment in the Department of Electrical and Computer Engineering and the School of Computing. At UNL Dr. Markvicka directs the Smart Materials and Robotics Laboratory, an interdisciplinary research lab that is creating the next generation of wearable electronics and robotics that are primarily composed of intrinsically soft materials (e.g. rubbers, gels, fluids). Dr. Markvicka has taught in the Department of Mechanical and Materials Engineering for four years, teaching classes in robotics, engineering controls, entrepreneurship, and machine learning. His interests include creating and evaluating novel experiential learning experiences that complement existing curricula. Before arriving at UNL, Dr. Markvicka received his B.S. and M.S. in Mechanical and Materials Engineering from UNL and his M.S. and Ph.D. in Robotics from Carnegie Mellon University.

Jason Daniel Finnegan
Kasey Moomau
Amie Sueann Sommers
Dr. Markeya S. Peteranetz, University of Nebraska, Lincoln

Dr. Peteranetz is the Learning Assessment Coordinator for the University of Nebraska-Lincoln College of Engineering. Her research interests include the impact of instructional practices on student learning and motivation, and sources of within-person variation in motivation and self-regulated learning.

Dr. Tareq A. Daher, University of Nebraska, Lincoln

Tareq A. Daher is the Director of the Engineering and Computing Education Core for the University of Nebraska-Lincoln, College of Engineering. Tareq earned his B.S in Computer Science from Mu'tah University in Jordan. He earned his M.A and PhD in Educational Studies with a focus on Instructional Technology at UNL. Dr. Daher collaborates with Engineering faculty to document and research the integration of innovative classroom instructional strategies in Engineering Classrooms, supports educational components of grants, facilitates data and assessment project, and delivers teaching-focused professional development for graduate students and faculty in Engineering. His work explores the role of implementing online, blended, and flipped models in enhancing instruction and learning in Engineering programs, while bridging quantitative and qualitative methods.

Designing learning experiences with a low-cost robotic arm

1 Introduction

The increasing popularity of robotics in STEM education can be attributed to its involvement in interactive and practical learning experiences, and its capacity to combine expertise and competencies from various disciplines, including computer science, electrical engineering, mechanical engineering, and mathematics. Robotics covers a wide range of fields and promotes the development of critical thinking skills such as problem solving, systematic reasoning, abstraction and generalization, as well as collaboration and communication [1, 2]. This growing interest in robotics has been accompanied by the development of accessible open-source platforms, such as Arduino and Raspberry Pi, which enable both novice and expert users to create electronic projects, from simple LED displays to complex robotic systems. This has resulted in the creation of several commercially available educational robotic platforms, including Lego Mindstorms and VEX Robotics, that can be integrated into existing curricula [3, 4], as well as custom open-source designs for robotic structures and controllers for robotic platforms [5, 6, 7, 8, 9, 10, 11, 12].

When selecting a robotics platform for STEM education, cost is one of the primary factors that is taken into consideration [3, 4]. In this paper, we will focus on robot arms that are constructed by connecting rigid bodies (known as links) together with rotational or prismatic joints. While there are several low-cost wheeled robotics kits available, such as the Balboa by Pololu (priced at $90), most low-cost robotic arms that cost less than $1,000 involve design and manufacturing tasks [5, 6, 7, 8, 9, 10, 11, 12]. These tasks are often outside the learning objectives of courses that cover the mechanics, planning, and control of robotic arms. Therefore, to provide a comprehensive and engaging learning experience that can be incorporated into various formative and summative assessments, the robotic arm needs to meet three key requirements: (1) *Affordability:* The robot arm should be affordable enough to enable each group of 2-3 students to have one. (2) *Portability:* The robot arm should be easy to transport the robotic arm to and from class or study groups. (3) *Untethered operation:* The robot arm should be able to operate without the need for wall outlets, allowing it to be used in a classroom, cafe, or park. By meeting these three requirements, the robotic arm will provide an ideal learning tool for students in STEM education, allowing them to gain hands-on experience regarding the mechanics, planning, and control of robotic arms.

Here, a robotic arm kit was introduced that is composed entirely of off-the-shelf components that can be assembled using a screwdriver and wrench. The assembled kit is low-cost (< $200), easily transportable in a small plastic toolbox, and can be powered utilizing a built-in battery or standard 5V USB cable (< 500 mA) connected to a laptop computer. This low-cost, transportable, and untethered robotics platform was used to evaluate the design of experiential learning experiences that complement existing robotics curriculum focusing on the mechanics, planning, and control of serial robotic arms. Student success rates for assessments with and without the robotic arm were analyzed in addition to perspectives of engineering students on the difference in assessment design and delivery over the course of one semester. We found that the learning activities on the robotic arm were more helpful than those without, and that students found high value in the hands-on experiences and real-world scenarios offered by the activities using the robotic arm.

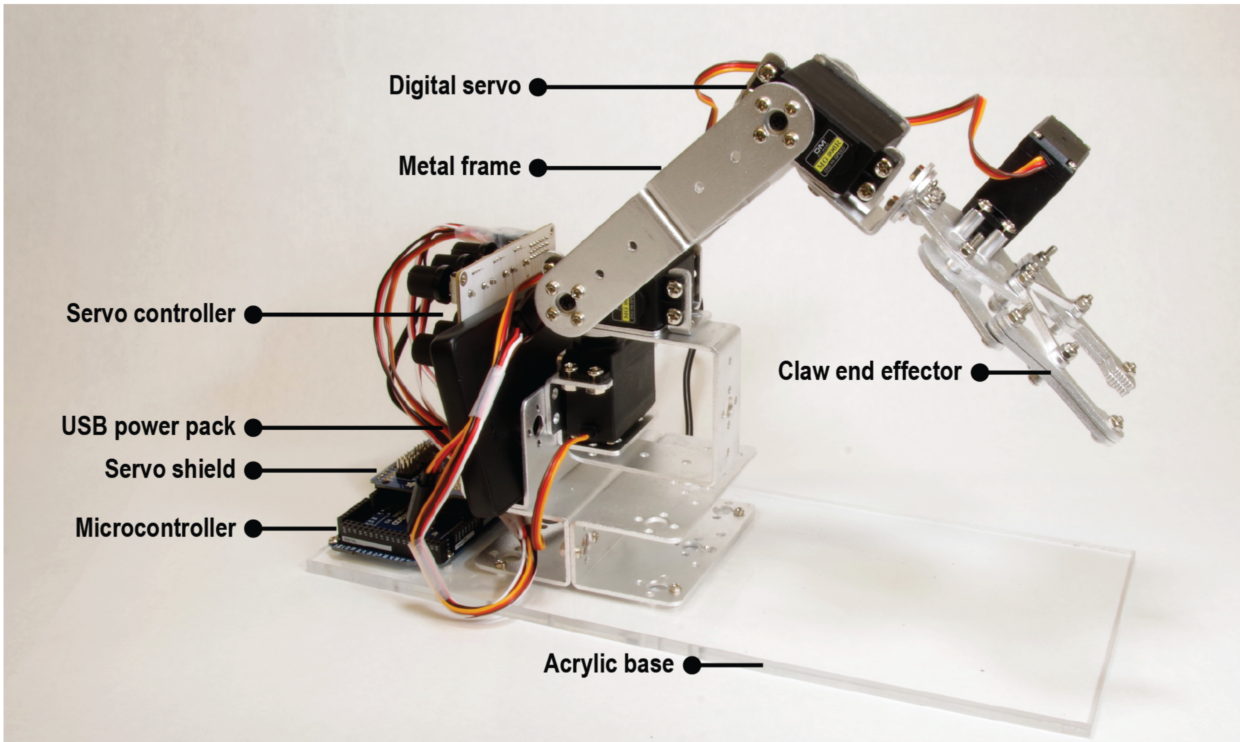

Figure 1: Photograph of the robotic arm kit with control electronics and power pack for untethered use in a classroom or general study environment.

2 Related research on affordable robotic arms for STEM education

One of the primary factors taken into consideration when selecting a robotics platform for STEM education is cost [3, 4]. Unfortunately, industrial robots priced at over $30,000 are often too expensive for many academic institutions to purchase. In addition to their high cost, industrial robots require dedicated space, pose safety risks, are expensive to maintain, and may cause scheduling constraints due to having fewer robotic arms than students. These limitations can reduce student engagement in hands-on activities, which are critical for effective learning.

Fortunately, there are several commercially available educational robotic platforms, such as Lego Mindstorms and VEX Robotics, which have been integrated into existing K-12 curricula. These platforms have a proven track record and are popular among educators and students alike [13, 14, 15]. However, these systems have limited complexity and are difficult to scale. In addition, these educational kits cost more than $1,000.

Alternatively, there are several low-cost open-source robotic arm designs that cost less than $1,000 [5, 6, 7, 8, 9, 10, 11, 12]. These designs provide students with the opportunity to design and build their own robots from scratch. However, these platforms involve design and manufacturing tasks that are often outside the learning objectives of courses that cover the mechanics, planning, and control of robotic arms.

3 Low-Cost robotic arm platform

In this section, we provide an overview of the hardware and software architectures of the low-cost robotic arm platform. The hardware is based on off-the-shelf components that can be easily found online and assembled using standard tools. The software was custom developed and open sourced [16]. The website also includes videos of course projects from previous offerings of the course.

3.1 Hardware architecture

The low-cost robotic arm kit, which is priced under $200, is comprised of a five-degree-of-freedom (DOF) serial robotic arm with a metal frame and a claw end effector (Figure 1). For our purposes, we only used the first three joints of the serial robotic arm. Each joint of the arm was driven using a high-torque, metal gear digital servo (MG996R). The kit includes the metal frame, servo motors, and metal servo horns, which can be assembled using standard tools like a screwdriver and wrench.

The robotic arm was controlled using an ATmega328 microcontroller (2488, Adafruit) and a 16-channel servo shield (1411, Adafruit) with a digital servo controller (NXP, PCA9685). The microcontroller can be connected to a computer, allowing commands to be sent over USB using programming languages like MATLAB. Additionally, a six-channel digital servo controller (Hiwonder) was included with potentiometers that enabled manual control the individual joints of the robotic arm. This manual servo controller was helpful for testing individual servos and identifying potential issues quickly.

The robot was powered using a laptop computer or portable USB power pack. This allowed for untethered use of the robot in a classroom or study environment, without the need for access to an electrical outlet or extension cord.

The robotic arm, electronics hardware, and portable battery was secured to an acrylic sheet (5×12 inch) using machine screws. Alternatively, double sided tape (VHB, 3M) could be used. For transportation, the entire kit was designed to fit inside a 14-inch toolbox (Akro-Mils, 09514CFT). This allowed students to securely transport the robot, cables, and any additional items to and from the classroom. A full list of the items included in the robotic arm kit can be found in Table 1.

The low-cost kit allowed us to purchase a kit for each student group (each group had three students) in the class, a total of 17 kits. By having an easily transportable kit, the student groups were able to bring the robotic arm to lecture or study groups, allowing for more hands-on learning experiences and flexibility in how we used the kit throughout the course.

3.2 Software architecture

The software architecture is illustrated in Figure 2. It is comprised of the following main components: (1) the serial robotic arm, (2) servo controller, (3) microcontroller with servo shield, (4) laptop computer with the Arduino integrated development environment (IDE) and MATLAB, and (5) optional sensor feedback interface. The robotic arm kit were powered using a laptop computer or USB power pack. A brief description of the different control methods is provided below:

Table 1: List of items included in the robotic arm kit.

Item	Manufacturer/Supplier	Part Number	Price
Robotic arm with servos	Diymore/Amazon	B095K61ZMQ	$80
Microcontroller (METRO 328)	Adafruit	2488	$18
16-Channel servo shield	Adafruit	1411	$18
Servo controller	Hiwonder/Amazon	B073XZH264	$17
USB power pack (5,000 mAh)	Insignia/Best Buy	NS-MB5MK21	$8
USB Cable, Male A to Bare Wire	CoolerGuys	840556071235	$1
Toolbox	Arko-Mils/Amazon	09514CFT	$20
Acrylic sheet	McMaster	4615T27	$10
		Total:	**$172**

A) Manual, individual joint control: The servos used in the robotic arm are connected to the six-channel servo controller from Hiwonder. The servo controller includes six potentiometers that control the corresponding six servos simultaneously. This control method highlighted the difficulty of joint control methods. It was also helpful for allowing the student groups to test individual servos and identify potential issues quickly.

B) Digital servo control: The servos used in the robotic arm are connected to the microcontroller via a servo shield that includes an I2C servo controller (NXP, PCA9685). A standalone program can be created and directly uploaded to the microcontroller. Commands are generated directly from the microcontroller. Using this control method, students can program the robotic arm to execute various tasks, such as pick-and-place operations or drawing shapes, allowing them to gain a deeper understanding of the mechanics, planning, and control of robotic arms. The program can be edited and re-uploaded as students refine their understanding of these concepts. This control method could be used to address all learning objectives of the course.

C) Digital servo control with computer interface: The servos used in the robotic arm are connected to the microcontroller via a servo shield that includes an I2C servo controller (NXP, PCA9685). Alternatively, the microcontroller and robot can be physically connected to a laptop computer by USB cable. This allows for a wider range of programming languages, including MATLAB, Python, C++, Java, and others, to be used to control the robotic arm. In this setup, commands are generated from the computer and transmitted to the microcontroller to control the robotic arm. The ability to use a laptop computer to control the robotic arm will allow for more sophisticated tasks to be executed, as the computational power of the computer can be leveraged to perform complex calculations and data processing.

For control methods A and B, skeleton code was provided to the student groups, enabling them to focus on specific learning objectives without getting bogged down in unnecessary details. For example when studying the inverse kinematics problem, students were tasked with creating a function that would compute the joint positions necessary to achieve a desired end-effector configuration. The provided skeleton code included the necessary supporting code to move the robot to the computed joint position. The code-base containing the skeleton code and supporting materials can be found at [16]. This approach allowed students to focus on key concepts and develop their programming skills.

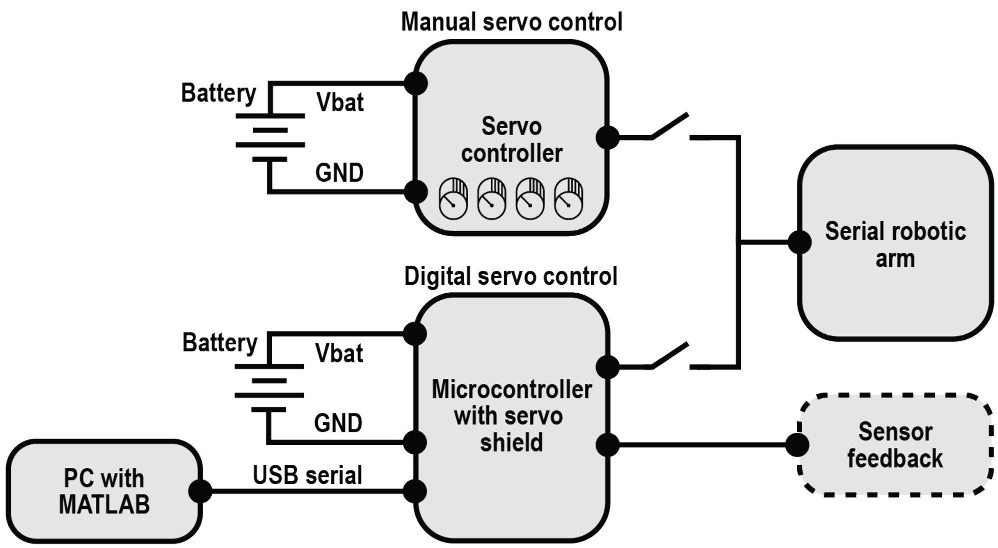

Figure 2: Schematic illustration of the robotic arm kit. The serial robotic arm can be manually controlled using a servo controller or digitally controlled using a microcontroller via a servo shield. Commands can be generated directly from the microcontroller, or a computer equipped with MATLAB or other software. The kit was powered using a laptop computer or USB battery pack to allow for untethered use in a classroom or general study environment.

4 Designing learning experiences with the robotic arm platform

4.1 Course overview

MECH 453/853, Robotics: Kinematics and Design, provides an introduction to robotics with a focus on the mechanics, planning, and control of serial robotic arm. The course covers methods for representing the position, orientation, and motion of rigid bodies, including parts, tools, and the mechanism itself. These concepts are applied to real-world applications such as manufacturing, surgery, and repair and maintenance in challenging environments like space. The course has been offered at the University of Nebraska-Lincoln for over 15 years, and its primary learning goals include:

- **LG1** *Rigid body motion:* Represent the orientation and position of a rigid body in space with respect to a fixed coordinate system.
- **LG2** *Forward kinematics:* Compute the orientation and position of a robotic arm given the joint angles.
- **LG3** *Inverse kinematics:* Compute the set of joint angles that will achieve a desired orientation and position of the end effector or tool.
- **LG4** *Velocity kinematics:* Relate the joint linear and angular velocities to the end-effector linear and angular velocities.
- **LG5** *Trajectory generation:* Compute a trajectory that describes the desired motion of a robotic arm in multidimensional space.

To assess students' learning, a combination formative and summative assessments were utilized. The formative assessments primarily focused on formal written activities with coding exercises to create subroutines to validate and automate the written activities. The summative assessments were exam based.

The robotics course is cross-listed and offers credit at both the undergraduate and graduate level. Historically, the class size is comprised of 40 senior undergraduate students and five graduate students. A majority of the students are from the Mechanical and Materials Engineering program with 1-3 students per year from another program in the College of Engineering such as Electrical and Computer Engineering or the School of Computing.

4.2 Integration of the robotic arm into the course learning goals and assessments

During the Fall 2021 semester, a robotic arm kit was designed and introduced to provide students with a hands-on learning experience and allow them to directly apply what they have learned in the classroom to real-world scenarios. The kit also exposed the students to embedded programming, which isn't traditionally covered in Mechanical Engineering programs. Two new assessments were introduced that complemented the existing formative assessments and evaluated the physical robotic arm, instead of CAD renderings existing or simulated robotic arms. The new assessments included formal written activities (*e.g.,* "Derive the inverse kinematics map for the three DOF robotic arm shown in Figure 1."), coding exercises to create subroutines for simulation and validation (*e.g.,* "Confirm your inverse kinematics solution using MATLAB or SolidWorks."), and coding exercises to guide students through a series of algorithms for controlling a serial robotic arm (*e.g.,* "Implement the inverse kinematics you previously derived using the provided skeleton code. Upload a video demonstrating the Cartesian control. Does the robotic manipulator work as expected? If not, describe potential challenges."). With the physical robotic arm, students were able to witness the challenges of joint space control, understand the physical limitations affecting the robotic workspace, and overcome the impact of joint backlash. These concepts are typically discussed at an abstract level, but with the use of a physical robotic arm, students could gain a deeper understanding of these topics and support the development of higher order thinking skills.

The course also included a semester long course project where student teams defined a problem statement, created a detailed mock-up of their design, built/purchased any necessary components, wrote algorithms to control the behavior of the robot, and finally tested their robot to ensure it functioned as expected. The student teams were asked to create a short video presentation to showcase their robot and its capabilities as well as any challenges they had encountered and how they overcame them. A growing collection of videos from previous course projects have been posted online [16].

5 Methods

5.1 Survey data collection

To assess student perceptions and experiences of the course and using the robotic arm, we asked students enrolled in *MECH 453/853: Robotics: Kinematics and Design* at the University of

Nebraska-Lincoln during the Fall 2021 semester to complete a series of survey questions. The survey contained six open-ended questions regarding students' perceptions and experiences of the course overall (*e.g.,* "Which learning activity in MECH 453/853 was most helpful to your learning?"), five open-ended questions regarding the activities that involved using the robotic arm (*e.g.,* "Were the learning activities that involved the robotic arm more helpful, less helpful, or comparable to your learning compared to activities that did not include it? Please elaborate."), and three Likert Scale style questions asking students to rate their perceptions of how useful, interesting, and impactful the robotic arm was in their learning and career plans (*e.g.,*"How interesting do you think it was to use the robotic arm for learning activities?") [17]. We structured the survey in this way to provide students an opportunity to discuss the robotic arm unprompted first, before we specifically addressed those activities. We conducted this survey at the end of the semester, prior to final exams to assess students' complete experiences of the course. As part of the consent process, participants had the opportunity to grant access to assignment grades to be used in the research. Thirty-six participants consented to having their assignment grades included in the research. All data collection and assessment methods described herein are approved under IRB #20211121456EX.

5.2 Course assignments

Grades were analyzed for four different assignments done throughout the course. Two of the assignments (Assignments 2 and 4) required students to use the robotic arm and two were more traditional assignments (Assignments 1 and 3) that did not incorporate the robotic arm. The assignments were worth different numbers of points based on the number of steps and questions involved, so the analysis was done on students' percentage scores for each assignment.

5.3 Analysis

Quantitative analysis was conducted in SPSS v. 25. All qualitative coding analysis was conducted in MAXQDA Plus 2022 (Release 22.2.0). We analyzed survey responses from students (n = 35, 78% response rate) using a descriptive and thematic coding cycle method [18, 19]. First, we briefly read through each survey response and descriptively coded them based on the topic of the response, rather than the content. Next, we used thematic coding methods to code each response based on content. Finally, we categorized these codes into emergent themes for interpretation [18, 19].

6 Evaluation

6.1 Qualitative analysis and results

Here we organize our findings by students' perceptions and experiences to the course in general, the specific activities that used the robotic arm, and the potential impacts of the course and robotic arm on their future career aspirations. All student responses we include here are examples that represent the general themes we found in our analysis, and have been de-identified such that students remain anonymous. A summary of our findings can be found in Table 2.

Table 2: A summary of the findings from our qualitative analysis, including the general course takeaways, robotic arm activity takeaways, and impacts on career outlook and decisions, as identified by students' survey responses.

Survey Questions	*Summary of Findings*
General Course Takeaways	• The robotic arm activities were the most helpful aspect of the course. • Students also found in-class example problems, homework, and group projects to be helpful. • Some students thought there should be more real-world examples in lecture and found there to be an overload of course content.
Robotic Arm Activity Takeaways	• The most common reason for why the robotic arm activities were "more helpful" than other course activities was because of the real-world applications and hands-on experience they provided. • Students said the robotic arm activities helped them better understand course content. • A small number of students indicated the robotic arm activities were "less helpful" than other activities, primarily citing a lack of prior knowledge and understanding regarding the coding and programming of the robotic arm, and a lack of time to complete the project.
Impacts on Career Outlook and Decisions	• Most students' career plans did not change after taking this course, including 1) those who were already interested in a career in robotics and continued to pursue that career plan after completing the course, and 2) those who were not considering a career in robotics and their plans remained unchanged after taking this course. • A small number of students' career plans did change after taking this course, including 1) those who were not considering a career in robotics prior to taking this course and indicated they would now like to pursue a career in robotics, and 2) those who were interested in a career in robotics before and have changed their career plans away from robotics after taking this course. • Two students indicated that they used knowledge and materials from this course directly in the application process for a robotics-related job.

6.2 General course takeaways

Overall, students indicated that the robotic arm activities were the most helpful aspect of the course to their learning, followed by in-class example problems that utilized both the physical robotic arm in the kit and other existing or simulated robotic arms (*e.g.,* solving for the position and orientation of parts, tools, or robotic end-effector), homework, and group projects. Specifically, students said that these activities contributed most to their general understanding of course content, but that they also found the hands-on learning aspects of the activities and the real-world applications to be most beneficial, such as pick-and-place robots in modern manufacturing environments, the Shuttle Remote Manipulator System (SRMS) on the International Space Station (ISS) used for repair and maintenance in challenging environments, and robotic-assisted surgery used for increased precision in confined spaces. Interestingly, the latter two outcomes were most closely aligned with the robotic arm activities. For example,

> *"Setting up our joint limits, defining our inverse kinematics and finding out workspace was extremely helpful in my learning of the material. The ability to work hands on has been very helpful."*

Other aspects of the course that students found helpful were the muddiest point activities [20] in lecture, followed by the PowerPoint notes and the guest lectures.

Students identified several features of the course that were not helpful to their learning, most notably an overload of content material in lecture, the lecture formats, and not enough real-world examples in the lecture component of the course. For example,

> *"There was rarely a comfortable moment in this class. I never felt like I could step back and evaluate any major projects such as our final as I was either attempting to comprehend the new material or finishing the homework assignments."*

6.3 Robotic arm activity takeaways

Students overwhelmingly observed the robotic arm activities to be a 'helpful' component of the course. Indeed, when asked to rate the most helpful learning activity of the course overall (without prompting regarding the robotic arm), students cited the use of the robotic arm more frequently than any other activity. The most common rationale that students provided for saying the robotic arms were helpful to their learning was that they helped students better understand content from the lectures and other activities, and the real-world applications of the robotic arm. For example,

> *"Yes, they helped me visualize how the theory in class could realistically be applied, as well as what unexpected problems might occur using a real interface",* and

> *"Yes, because it's one thing to understand the theory and a completely different thing to implement and troubleshoot in reality."*

When asked to compare the robotic arm activities to other course activities, most students rated the robotic arm activities as 'more helpful', again, most frequently citing the real-world applications of these activities and the hands-on experience. For example,

> *"Activities involving the arm were more helpful, as it gives a hands-on experience and introduces issues that are faced in real world scenarios."*

Some students indicated the robotic arm activities were less helpful than other course activities, most commonly citing a lack of prior knowledge, and a lack of time to complete a project. In this vein, when asked to describe their experiences using the robotic arm, the negative experiences were mostly focused on a lack of understanding regarding the coding and programming of the robotic arm, and the rushed nature of the group project. For example,

> *"It was difficult to code for, especially to someone unfamiliar with the course",* and

"I think the arm was poorly integrated into the schedule of this class. If we had started using it within the first few weeks, spent more time learning about the code and other things we could do with the arm, it would have been very helpful. We however have no time to do anything impactful with the arm as we only have a few weeks during exam season of our busiest year to work on our project."

6.4 Impacts on career outlook and decisions

Student responses regarding their career aspirations were closely aligned between the career questions that were asked in context of the course overall and in context of the robotic arm activities (some students referenced their answers to the course-focused career questions earlier in the survey when answering the robotic arm career questions), so these findings are presented together here.

Most students who completed the survey indicated that they were already interested in a career in robotics, and this course did not change their thinking. For example,

"This course has not changed my plans, but it has informed them. I feel that I have more knowledge of what an engineer actually does when designing robotic systems, which makes me more confident in my goal."

The next most common survey responses were from students who were not interested in a career in robotics prior to taking this course, and remain unchanged in that career decision. For example,

"It has me more interested in robotics more than previously, but not enough to go into it."

Following students whose career plans remained unchanged are those who decided to pursue a career in robotics after completing this course. For example,

"Yes, I have found a new passion for robotics, specifically in implementation of kinematics in robotic design. I plan to work in a robotics centered field after the completion of a graduate degree in Robotics."

Finally, there were a few students who indicated this course contributed to changing their career plans away from robotics. For example,

"They showed me that programming a robotic arm is not the area of robotics I want to go into. While they are cool to use, the specifics that go into programming them and designing a good workspace are not topics I am interested in."

Notably, two students indicated that they used materials and knowledge gained from this course directly in applying for jobs. One student indicated that they had already intended to pursue a career in robotics, but another indicated that this course changed their career plans to a robotics-focused career. These students stated,

"Talking about this class in an interview helped me land a job involved in robotics.", and

"Yes! I have loved the material and applications, I applied for a job in the robotics field, and I'm waiting for a response."

6.5 Quantitative results

All 36 participants who consented to having their assignment grades used for the research submitted work for all four assignments. Participants scored highly on all four assignments: the average percentage for each was at the 'A' level based on the university's typical grading scale. Repeated-measures analysis of variance (ANOVA) was used to test for differences in assignment performance based on assignment type (traditional vs. robotic arm) and timing in the semester (early vs. late). The main effect of assignment type was not significant, Wilks' $\Lambda = 0.897$, $p > 0.05$. The main effect of timing in the semester was significant, Wilks' $\Lambda = 0.580$, $p < 0.01$, with students scoring lower on assignments later in the semester. The interaction between timing and assignment type was not significant, Wilks' $\Lambda = 1.00$, $p > 0.05$. These results indicate that students performed at similarly high levels on class assignments regardless of whether those assignments followed more traditional questions and problem solving or if they were based on the robotic arm.

7 Conclusion

The robotic arm kit provided a low-cost, mobile testbed that could be easily transported to and from the classroom, providing a novel experiential learning experience that guided senior undergraduate and graduate students through a series of algorithms for controlling a serial robotic arm. The kit also supported the development of higher order thinking skills, including problem solving, systematic reasoning, abstraction and generalization, and collaboration and communication. Overall, the students found the robotic arm to be a 'helpful' component of the course and was the most helpful aspects that supported their learning. However, the lack of prior programming knowledge can be challenging.

Future work includes the creation of online asynchronous active learning experiences that cover programming of the robotic arm in greater detail to address identified knowledge gaps. In addition, we are currently working on adding sensors for feedback control such as a camera that can be paired with the robotic arm for machine vision applications. The camera would allow students to easily detect and track objects of interest in real-time.

Acknowledgements

We acknowledge support through the Nebraska Tobacco Settlement Biomedical Research Development Fund and NASA Nebraska Space Grant (#80NSSC20M0112).

References

[1] F. B. V. Benitti, "Exploring the educational potential of robotics in schools: A systematic review," *Computers & Education*, vol. 58, no. 3, pp. 978–988, 2012.

[2] M. S. Khine, M. S. Khine, and Ohmer, *Robotics in STEM Education*. Springer, 2017.

[3] R. Parameshwaran, S. P. Kumar, and K. Saravanakumar, "An integrated fuzzy mcdm based approach for robot selection considering objective and subjective criteria," *Applied Soft Computing*, vol. 26, pp. 31–41, 2015.

[4] S. Evripidou, L. Doitsidis, G. Tsinarakis, Z. Zinonos, and S. A. Chatzichristofis, "Selecting a robotic platform for education," in *2022 IEEE International Conference on Consumer Electronics (ICCE)*. IEEE, 2022, pp. 1–6.

[5] S. C. White, J. D. Farmer, and A. M. Eslami, "Engaging students' creativity through designing a low-cost educational robotic arm," in *2018 ASEE Annual Conference & Exposition*, 2018.

[6] A. Elfasakhany, E. Yanez, K. Baylon, R. Salgado *et al.*, "Design and development of a competitive low-cost robot arm with four degrees of freedom," *Modern mechanical engineering*, vol. 1, no. 02, p. 47, 2011.

[7] A. Yousuf, C. C. Lehman, M. A. Mustafa, and M. M. Hayder, "Low-cost robot arms for the robotic operating system (ros) and moveit," in *2016 ASEE Annual Conference & Exposition*, 2016.

[8] I. I. Basith and B. Marroquin, "Byoe: Design and development of a simple robotic arm," in *2020 ASEE Virtual Annual Conference Content Access*, 2020.

[9] C. C. Mouli, P. Jyothi, K. N. Raju, and C. Nagaraja, "Design and implementation of robot arm control using labview and arm controller," *IOSR Journal of Electrical and Electronics Engineering*, vol. 6, no. 5, pp. 80–84, 2013.

[10] K. Jahnavi and P. Sivraj, "Teaching and learning robotic arm model," in *2017 International Conference on Intelligent Computing, Instrumentation and Control Technologies (ICICICT)*. IEEE, 2017, pp. 1570–1575.

[11] R. L. Avanzato, "Development of a matlab/ros interface to a low-cost robot arm," in *2020 ASEE Virtual Annual Conference Content Access*, 2020.

[12] D. Rivas, M. Alvarez, P. Velasco, J. Mamarandi, J. L. Carrillo-Medina, V. Bautista, O. Galarza, P. Reyes, M. Erazo, M. Pérez *et al.*, "Bracon: Control system for a robotic arm with 6 degrees of freedom for education systems," in *2015 6th International Conference on Automation, Robotics and Applications (ICARA)*. IEEE, 2015, pp. 358–363.

[13] A. Sirinterlikci, J. McKenna, and L. Harter, "Vex v5 workcell: Industrial robotic arm model for stem education (other)," in *2022 ASEE Annual Conference & Exposition*, 2022.

[14] V. Román-Ibáñez, F. A. Pujol-López, H. Mora-Mora, M. L. Pertegal-Felices, and A. Jimeno-Morenilla, "A low-cost immersive virtual reality system for teaching robotic manipulators programming," *Sustainability*, vol. 10, no. 4, p. 1102, 2018.

[15] I. M. Souza, W. L. Andrade, L. M. Sampaio, and A. L. S. O. Araujo, "A systematic review on the use of lego® robotics in education," in *2018 IEEE Frontiers in Education Conference (FIE)*. IEEE, 2018, pp. 1–9.

[16] "MECH 453/853: Robotics: Kinematics and design," https://smr.unl.edu/MECH453-853.

[17] R. Likert, “A technique for the measurement of attitudes.” *Archives of psychology*, 1932.

[18] J. Saldaña, “The coding manual for qualitative researchers,” *The coding manual for qualitative researchers*, pp. 1–440, 2021.

[19] B. Miles Matthew, H. A. Michael, and S. Johnny, “Qualitative data analysis: A methods sourcebook,” 2014.

[20] A. Carberry, S. Krause, C. Ankeny, and C. Waters, ““unmuddying” course content using muddiest point reflections,” in *2013 IEEE Frontiers in Education Conference (FIE)*. IEEE, 2013, pp. 937–942.