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METHODS

An Inexpensive Autonomous Mobile Robot for Undergraduate Education: Integration of Arduino and Hokuyo Laser Range Finders

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This work involved human subjects or animals in its research. The authors confirm that all human/animal subject research procedures and protocols are exempt from review board approval.

ABSTRACT This paper discusses how to integrate a widely used, inexpensive laser range finder (LRF), the Hokuyo URG-04LX-UG01, with an easy-to-use Arduino microcontroller, into a science, technology, engineering, and mathematics (STEM) program for mechanical engineering students. The LRF has been used in several autonomous robots, in conjunction with laptops and desktop computers, due to its low cost. In addition, Arduino microcontrollers are suitable for educational purposes due to their open-source design and cost-effectiveness. Thus, combining the Hokuyo LRF with Arduino microcontrollers seems to be the best option to teach mechatronics to undergraduate students majoring in non-electrical and electronic engineering subjects, such as mechanical engineering. However, they have seldom been integrated for use in STEM education. Here, we built an autonomous robot integrating these devices and designed a course that teaches several aspects of mechatronics, including control engineering, programming, and embedded systems. The course for mechanical engineering students is 10 weeks in duration, easy to implement, and has a high cost-benefit ratio given the low cost of the robot (∼1,350 USD). The results of a questionnaire given to the student participants upon completion of the course indicated that the course enhanced their knowledge, motivation, interest, and satisfaction. Therefore, we believe that this report will be helpful in providing a STEM education framework that allows students to acquire the basic skills and knowledge necessary to solve real-world problems.

INDEX TERMS Course assessment, course design, higher education, LiDAR, LRF, microcontroller, mobile robot, STEM, undergraduate.

I. INTRODUCTION

Science, technology, engineering, and mathematics (STEM) is a major focus in Japan, and the Ministry of Education, Culture, Sports, Science and Technology requires all elementary schools to provide technical education, such as computer programming and electronics. Recently, the use of the arts as an enhancer of the educational experience has been incorporated into STEM education. The main objective of STEM education is to develop students' skills in autonomous learning, innovation, decision-making, and problem-solving through experience. In the context of engineering, STEM education should increase students' understanding of how things work and improve their use of technologies [1]. However, university graduates have reported that some engineering science courses are not useful, due to their

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lack of applicability to professions outside the engineering sciences [2].

In mechanical engineering, the gap between theory and practice often seems wider than in other engineering fields, because traditional mechanical engineering education is based around the study of dynamics, i.e., mechanics, materials, fluid, and thermodynamics. The complexities of the instrumentation and control systems require interdisciplinary knowledge (e.g., [3]) of electrical engineering, electronics, and information technology; however, these areas are seldom covered in any depth in mechanical engineering curriculums. Thus, mechanical engineering education has often fallen below expectations, despite clear demand, leaving mechanical engineering graduates at a considerable disadvantage in the job market. Especially in Japan, it is not uncommon that undergraduate students do not learn computer programming until they join labs for their graduation research in standard mechanical engineering departments.

Mechanical engineering education is traditionally based on classroom learning, with experimental and practical teaching conducted in groups. Self-education, including trial and error learning, has presented challenges due to safety concerns. In contrast, project-based learning (PBL) has been encouraged in engineering fields [4]. Furthermore, case studies can improve students' critical thinking, problem-solving, and higher-order thinking skills, as well as their conceptual understanding and motivation to learn [5], [6]. It has been reported that microcontrollers are useful tools for PBL [7]. Microcontroller-based devices and appliances are important in all aspects of everyday human life and in automated industries. The recently developed, inexpensive, open-source Arduino microcontrollers (Arduino, Turin, Italy) are useful in many laboratory environments [8] and for prototyping [9]. In addition to their low cost, these microcontrollers can be used by individuals with modest programming and electronics skills, such as mechanical engineering students.

Robots can help achieve learning objectives [10] and are suitable for STEM education [11]. In particular, mobile robots are important for PBL in the context of undergraduate education, as they have become more commonplace in commercial and industrial settings, including military and security environments. Moreover, the core technologies of mobile robots are the same as those of autonomous cars [12], as they are based on laser range finders (LRFs) [13]–[15]. LRFs have been used in a broad range of applications, including those involving localization, obstacle avoidance, range detection, pattern detection, and mapping [16]. Although LRFs are generally costly, recently, inexpensive LRFs have been used in autonomous robots. One inexpensive LRF, the URG-04LX-UG01 (Hokuyo Automatic, Tokyo, Japan), is now the most popular among robot designers, due to its low cost of about 1,000 USD, compactness, and low weight [17]. The Hokuyo URG-04LX-UG01 also exhibits a repeatability that is comparable to the LMS 200 (Sick, Waldkirch, Germany), which has a price of 6,000 USD [18]. Combining the Hokuyo LRF and Arduino boards provides an optimal system for building inexpensive robots for educational purposes; however, integration of these devices has not been widely reported.

This paper discusses how to use the Hokuyo LRF, URG-04LX-UG01, in conjunction with Arduino microcontrollers, to build an inexpensive autonomous robot. We show how this can be applied to mechanical engineering education for undergraduates as a 10-week course. The course materials and programming codes are available on GitHub (https://github.com/yuki-ueyama/NDA-Mobile-Robot) and the course is easy to implement. Our questionnaire assessment showed the robot build project and the associated program were well received by mechanical engineering students.

II. RELATED WORK

Given that robotics offer enormous potential as a learning tool [19], there have been a number of approaches to bring robots into the forefront of education curriculums. This chapter reviews the literature on educational robotics and course development.

A. EDUCATIONAL ROBOTICS

Social robotics is a major component of educational robotics. Social robots can serve as tutors or peer learners. They enhance cognitive and affective outcomes; they are as good as human tutors in certain situations [20]. For example, they have been used for pre-tertiary education (e.g., [21]–[23]) and also as a tool for improving the social skills of children with autism spectrum disorder [24]. However, there are limitations with respect to successfully applying social robots to real-life classroom settings, with ethical and safety concerns as ongoing issues [25].

On the other hand, it has been suggested that robotics can easily facilitate discussions in STEM education [26, 27], including computational thinking [28]. This is due mainly to the difference between robots and computers in aspects of full embodiment, as it is much more appealing to interact with robots than with software. With the objective of introducing robots to STEM education, several types of robots have been developed for both commercial and non-commercial purposes [29]–[32]. LEGO Mindstorms (LEGO, Billund, Denmark) may be one of the most successful commercial robot platforms for education, given its ability to target a wide audience ranging in age from elementary to undergraduate students. There have been many reports about LEGO Mindstorms as an effective tool for engineering education including data acquisition, and real-time control system design [33]. It can easily fulfill several STEM requirements at the undergraduate and postgraduate academic levels.

Building robot kits with structured materials increases students' awareness of the robotization of machines [34]. However, unfortunately, such robot kits do not usually allow for, nor support, modifications to their electrical and mechanical systems. Thus, having to use the original programming tools and user interfaces induces a lack of versatility and often limits education curriculums that use such embedded systems, even though there are some benefits in its ease-of-use for novice learners [35].

Versatility and compatibility are necessary to support long-term learning and a shift to mainstream industrial requirements [36]. As such, open-source design has become increasing popular as one of the most important concepts in development robotics platforms for higher education [29]. The open-source concept provides better compatibility with standard programming environments and greater flexibility regarding hardware modifications. Moreover, teachers have better accessibility to various tools for exploring and teaching a wide range of topics such as mechanics, electronics, and software. As an example, the TurtleBot series (Robotis, Seoul, Korea) of commercial robots have adopted an open-source design [31].

Although numerous educational robots have been developed and some of them are available commercially, questions remain as to how an educator goes about choosing the best robotic tool from several candidates to achieve an educational purpose. A previous study proposed a framework to support the development and evaluation of educational robots targeted for use in formal education settings [37]. However, the costs of the educational robots have remained the greatest barrier to deciding whether to introduce them and, thus, have limited widespread adoption in various educational settings and objectives [29], [30], [38], [39].

B. COURSE DEVELOPMENT

Robotics is a multidisciplinary yield that includes mechanical engineering, electrical and electronic engineering, and computer science. Specifically, it is an aggregate of three core knowledge areas [40]: control engineering, programming, and electronics including embedded systems. These core areas are directly related to the design of STEM courses in mechanical engineering departments.

Control engineering is an area of knowledge with significant mathematical content, including differential equations, linear algebra, differential geometry, and complex variables, among others, and the subject matter tends to be difficult for most students [41]. Thus, it has been reported that experimental and practical-based teachings are more effective than classroom-based ones to gain a better understanding of the theoretical aspects [42]. Several educational robotics tools have been developed to address these educational needs, with the expectation of motivating students more effectively [43], [44].

Previous studies have reported that the most frequently cited skills necessary for learning programming are related to problem solving and mathematical ability, followed by motivation and engagement, given the difficulties in learning the syntax of programming languages [45]. Educational robots can be used as alternative tools to embody computational concepts in programming education [32]. Robot programming is effective in the acquisition of programming concepts, and it can enhance students' descriptive abstraction and motivation more effectively [30], [46]. In particular, several studies have suggested that the learning-by-teaching methodology through games and competitions can be used to promote computer science, including programming starting in the primary years and continuing through undergraduate studies [47]–[49].

A knowledge of embedded systems could be acquired through robot prototyping and construction, and fitted to an adaptation of PBL [7]. Robotics education including prototyping has had a significant impact on students' academic outcomes with respect to incorporating interdisciplinary knowledge and instilling the technical and professional skills required in pursuing a successful career [10]. The curriculum is organized such that the students can systematically solve real-world problems.

Most of the previous studies have focused mainly on solution proposal and evaluation of individual problems. On the other hand, curriculum content and assessment have had a broader focus [50].

C. MOTIVATION FOR THIS WORK

Cost has been the most important factor limiting the introduction of robots into STEM education. The integration of the Arduino microcontrollers and Hokuyo LRF has not been widely reported, although they are known to be useful tools with respect to their price point and performance. Yet, there have been few reports addressing the effectiveness of curriculum content in STEM education. Thus, we consider the following two questions as the motivation for this research: 1) Is it possible to integrate the Arduino microcontrollers and the LRF as mobile robots for implementation in undergraduate education curriculums? and 2) Does the combination have educational effects?

To answer these questions, this work was conducted as part of an undergraduate education course in the Department of Mechanical Engineering at our institution, the National Defense Academy of Japan (NDA). We developed the course using an inexpensive autonomous mobile robot, based on Arduino microcontrollers and Hokuyo LRFs. After the end of the course, we examined the outcomes in terms of technical knowledge, motivation, interest, and satisfaction using a questionnaire. The course materials and codes are freely available online. It is our hope that others in the field will find the information helpful for designing mechanical engineering curriculums.

III. MATERIALS AND METHODS

A. INEXPENSIVE AUTONOMOUS MOBILE ROBOT

The inexpensive autonomous mobile robot includes the Hokuyo LRF, located on a three-dimensional (3D)-printed acrylonitrile butadiene styrene (ABS) plate, assembled on an Arduino microcontroller-based robotic platform (Omnirover 3WD; Vstone, Osaka, Japan; Fig. 1a-b). The robot was

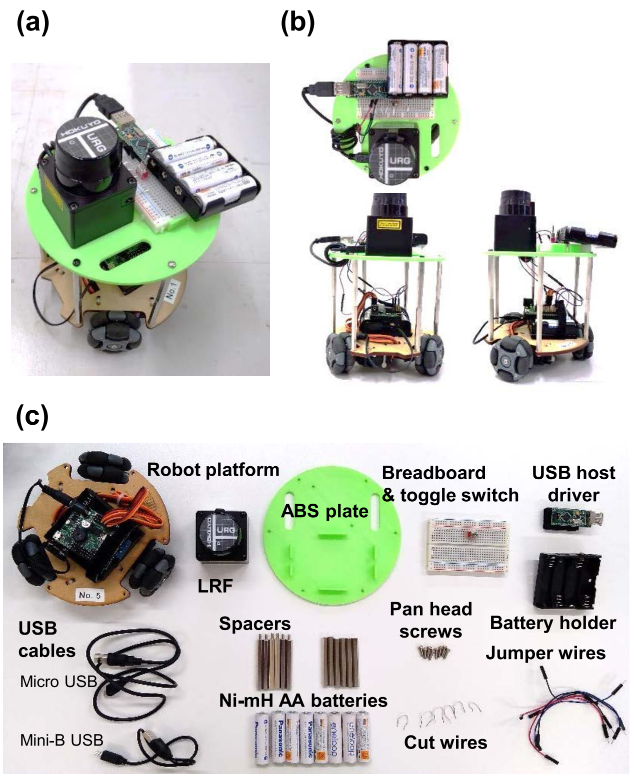


FIGURE 1. Inexpensive autonomous mobile robot: (a) overview and (b) three-dimensional view. (c) Twelve components of the robot. LRF: laser range finder; ABS: acrylonitrile butadiene styrene; USB: universal serial bus.

TABLE 1. List of autonomous mobile robot components and prices.

Item	Model (Brand)	QTY	Cost (USD)
Laser range finder	URG-04LX-UG01 (Hokuyo Automatic)	1	1,080
Robotic platform	Omnirover 3WD (Vstone)	1	120
USB host driver	VDIP1 (FTDI)	1	23
Ni-MH AA battery	Eneloop 4 pics (Panasonic)	2	40
5-cm spacer	Internal-external	6	30
	Internal-internal	6	30
USB cable	Micro USB	1	5
	Mini-B USB	1	5
Pan head screw	M3 8 mm	8	5
Breadboard	55 mm × 85 mm	1	3
Battery holder	For four AA batteries	1	2
Toggle switch	Breadboard-friendly	1	1
Jumper wire	Internal-external	6	1
Cut-wire	Cut to 20 mm	6	–
ABS plate	Custom-made	1	–
Total			1,345

composed of 12 parts (Fig. 1c). The parts were assembled using hex spacers and pan head screws. The robotic platform is equipped with three omni-wheels and a control board (V-duino VS-RC202; Vstone) including a microcontroller (ESP-WROOM-02; Espressif Systems, Shanghai, China). The robotic platform costs 120 USD (TABLE 1), but it is not too inexpensive compared to other successfully used low-cost mobile robot platforms costing 125 USD (under an exchange ratio of 1 USD = 0.8 GBP) [29] and another of less than 25 USD [39]. In our design, the board is compatible with Arduino and does not depend on a specific robotic platform. The program codes can be written using the Arduino IDE development tool. Thus, our source codes are editable and easy to modify for use with other Arduino microcontrollers. The robot can move in all directions via the three omni-wheels actuated by servo motors and the control board. The above specification is not essential; the robot can be substituted with others that have Arduino microcontrollers.

The Hokuyo LRF is designed for ease of use as the power source; data transfer occurs through a USB interface. Although direct connection of this product with a laptop or desktop computer is straightforward [51], communication between the Hokuyo LRF and Arduino microcontrollers has not been widely reported because Arduino boards do not have a USB interface for external inputs, excluding communication with personal computers. Thus, we used a USB host driver (VDIP1; FTDI, Glasgow, UK) to convert the output data of the LRF to a serial communication protocol, i.e., UART, which is compatible with Arduino microcontrollers (Fig. 2a). The connections were wired on a breadboard using jumper wires (Fig. 2b-c). We confirmed that this configuration was also valid for other Arduino microcontrollers. Note that the latest firmware of the USB host driver VDIP1 may not work properly; if this occurs, the firmware can be downgraded to version 3.64, which has been confirmed to work well.

The total cost of each robot was almost 1,350 USD, including the Ni-MH AA batteries but not the battery charger (TABLE 1). In our configuration, the robot operated continuously for about 60 min using battery power. A previous study reported that 3,300 USD was required to construct an inexpensive robot for student education applications, excluding the power supply, motor, and sensors [38]. Our setup was more cost-effective than other autonomous robot construction projects, although 80% of the total cost was attributable to the LRF.

B. COURSE DESIGN

We developed a course enabling mechanical engineering students to understand basic concepts pertaining to embedded systems and mobile robotics and then had them apply these concepts in practice. The course emphasizes practical, rather than theoretical application of mechatronics technology to solve engineering problems, in accordance with a past report [52], with an overall aim of integrating actuators, sensors, controls, and embedded systems into a PBL framework to help students learn about these technologies over a short period.

The course was designed for students majoring in mechanical engineering, most of whom had not attended any classes

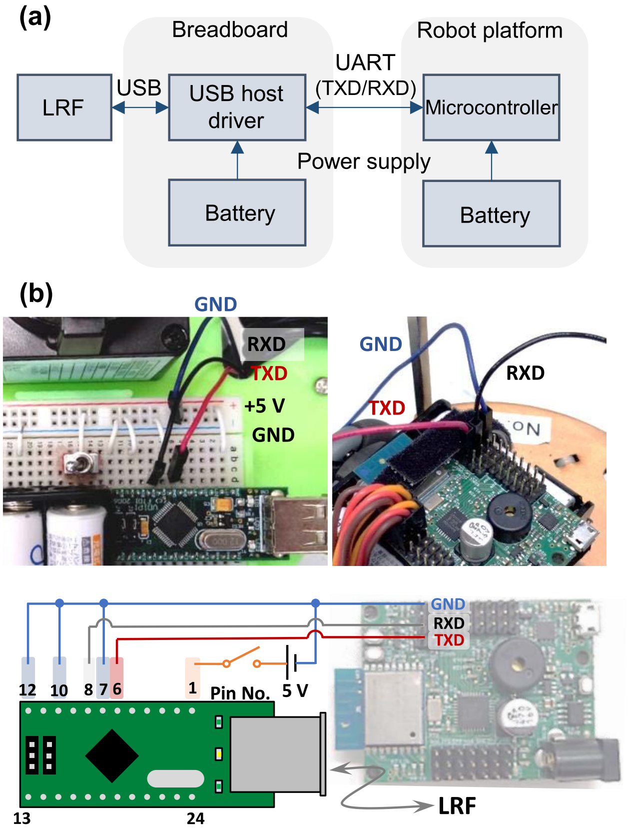
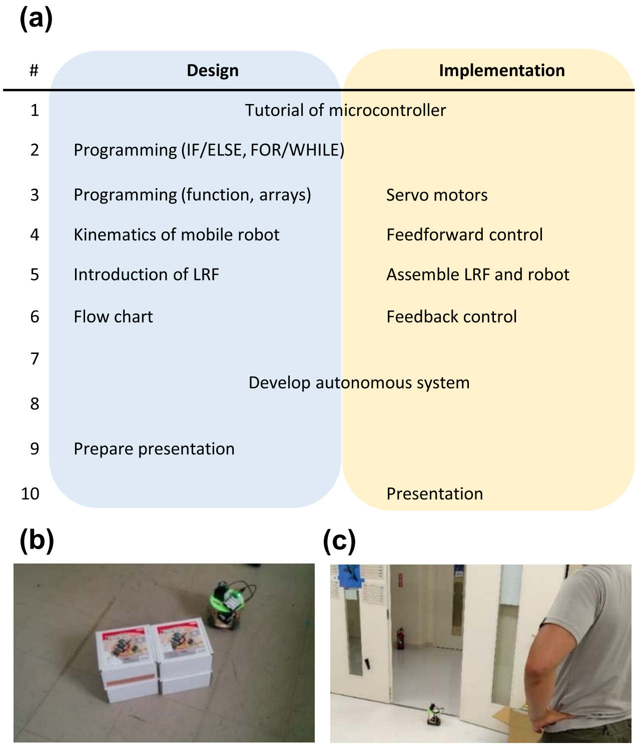


FIGURE 2. Communication between the LRF and microcontroller. (a) Schematic diagram of the communication pathways between the LRF and microcontroller. UART: universal asynchronous receiver/transmitter. (b) Actual wire connections (top) and the schematic diagram (bottom) between the LRF (via the USB host driover on the breadboard) and the microcontroller.

in electrical, electronic, or computer engineering (including computer programming), but they had learned the basics of control engineering and mechanical dynamics via classroom lectures. The course goals were to construct an algorithm, experience easy electronic work, and obtain an understanding of feedforward and feedback controls. These goals were introduced at different points during the course, targeted at the development of an autonomous control system. After the course, we administered a questionnaire to assess the effects.

The students were required to design and develop an autonomous mobile robot system. This necessitated an understanding of the technological basis for unmanned mobile vehicles and autonomous driving systems. Course components included embedded programming, as well as learning about instrumentation and control techniques for LRFs. Alternating course design and implementation is desirable [53]. Our course was 10 weeks in duration, as stated above, with one 90-min class held once per week (Fig. 3a). From the first through the sixth week, the course was provided as a lecture that focused on basic programming practices and robot control systems. From the seventh week, the students started a project and prepared their presentations under the supervision of at least one tutor. However, the students were given laboratory access to practice their skills and enhance their understanding for successful completion of the final project. The difficulty of the course could be modified by adjusting the class timings. The learning objectives and content of each class were as follows:



#	Design	Implementation
1	Tutorial of microcontroller	
2	Programming (IF/ELSE, FOR/WHILE)	
3	Programming (function, arrays)	Servo motors
4	Kinematics of mobile robot	Feedforward control
5	Introduction of LRF	Assemble LRF and robot
6	Flow chart	Feedback control
7	Develop autonomous system	
8		
9	Prepare presentation	
10		Presentation

FIGURE 3. Course program: (a) learning materials, (b) example obstacles requiring the coding of feedforward and feedback controls for circumvention with a robot (Supplementary Material S1.mp4), and (c) project work to develop the autonomous control system (supplementary material S2.mp4).

Week 1: Course objectives. The first course lecture introduces its aims and the learning materials. An overview of embedded systems using microcontrollers is provided, along with basic coding instructions regarding how to move a mobile robot.

Weeks 2–3: Embedded programming. Embedded programming based on the Arduino microcontroller is taught in lecture format. Topics covered include basic computer programming concepts, including conditional execution (i.e., IF and ELSE statements), iterative execution (i.e., FOR and WHILE statements), functions, and arrays. The students are required to input sample code by themselves, to develop their coding skills.

Week 4: Servo motors. The students are required to control servo motors using the programming techniques learned in the previous lessons. Then, they learn about the kinematics of the omni-wheel robot and must create feedforward control code to control the robot as it circles an obstacle (Fig. 3b).

Weeks 5–6: Feedback control using an LRF. The students learn about the mechanisms underlying the LRFs used in autonomous robots and cars and create code for feedback control of their robot using an LRF. They are also required to create code for the Arduino microcontroller allowing acquisition of sensor information by the LRF, and then embed it in the robot. The feedback control code should enable the robot to circle an obstacle, similar to the week 4 task. Finally, the students represent their algorithm in flowchart form.

Weeks 7–8: Project work. The teacher provides each student with a project, which requires the design and development of a control system to navigate a course with several obstacles (Fig. 3c).

Week 9: Presentation Preparation. The Students Prepare a Presentation to Summarize Their Ideas and Results

Week 10: Presentation and evaluation. Each student presents their project, including a demonstration of their robot navigating the course via the developed control system.

We have offered this program to fourth-year mechanical engineering students at NDA since 2019. The students at NDA are required to achieve both academic and military programs. The academic program is equivalent to a standard four-year university, and the students belong to a department from their second year after liberal studies in their first year. There is no difference in the academic curriculum of the mechanical engineering department between NDA and other typical universities in Japan.

C. PARTICIPANTS

In 2021, our course was attended and completed by nine students, making up 25% of the fourth-year students of the mechanical engineering department, and one robot was provided for each student. For this research, we asked all nine students to answer a questionnaire to assess the content; the students were all male and aged 21–24 years. Additionally, as a control group, we also asked nine other fourth-year students in the department at NDA, who did not attend the course, to complete a modified questionnaire. The students included one female, aged 21–22 years.

The questionnaires were filled out anonymously. We did not give them any details about this survey. They agreed to the publication of the data and provided written informed consent. However, ethical approvals were exempt, because our survey was in bearer form.

D. QUESTIONNAIRE ASSESSMENT

We developed a questionnaire for course assessment. The questionnaire was composed of 21 questions to evaluate "technical knowledge," "motivation and interest," "impression of difficulty," and "satisfaction" (Fig. 4, left). Notably, the students of the control group were asked to complete a modified questionnaire with only 14 questions for the evaluation of "technical knowledge" and "motivation and interest" (Fig. 5, left). The students were required to rate their answers on a 5-point scale (in which "1" represented "none" and "5" represented "very much"). The questions were determined in accordance with a previously reported format [33].

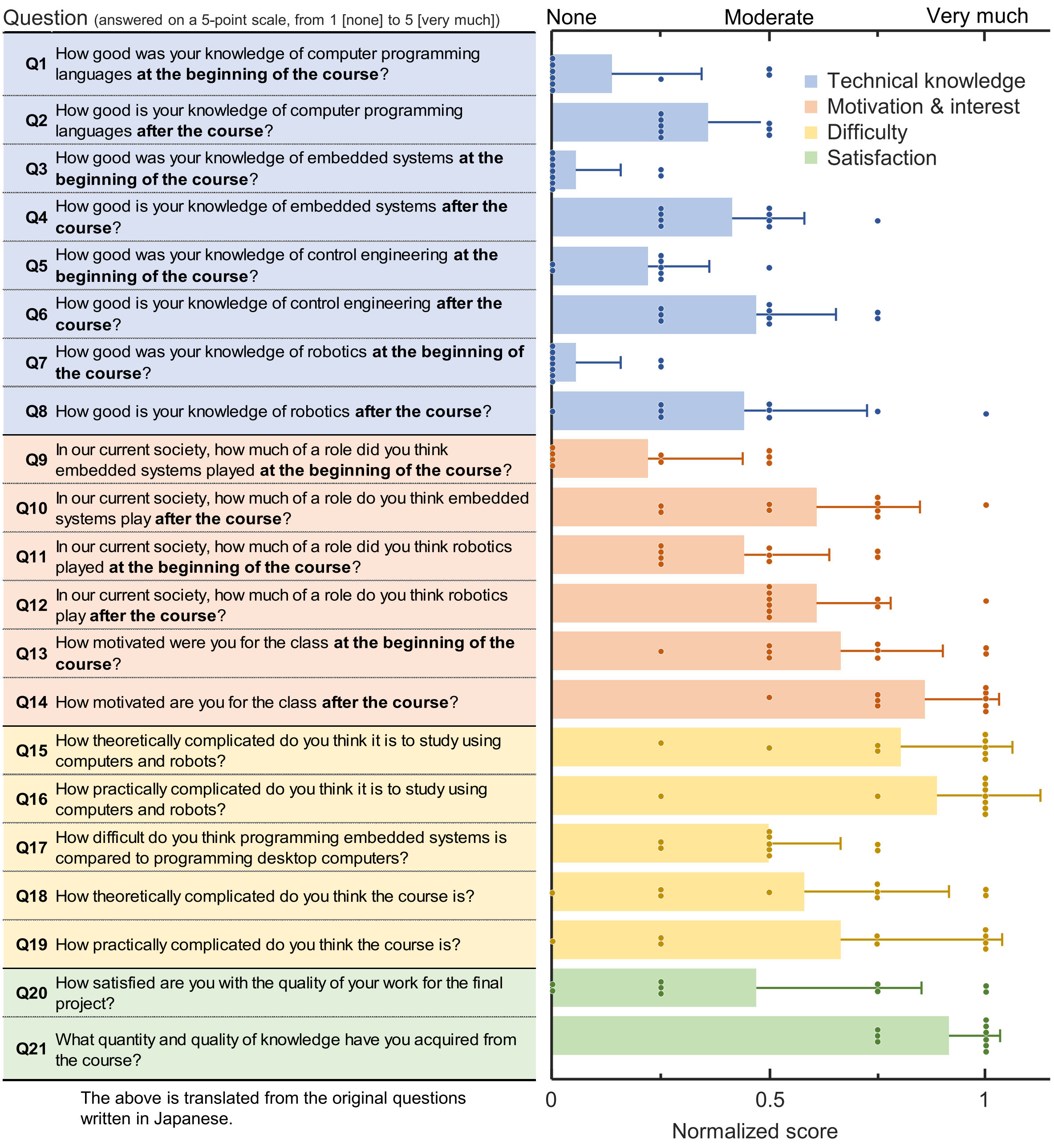
The answers obtained from the students in the attending group were categorized according to the purpose of each question: technical knowledge before (Q1, Q3, Q5, and Q6) and after the course (Q2, Q4, Q6, and Q8), motivation and interest before (Q9, Q11, and Q13) and after the course (Q10, Q12, and Q14), impression of the difficulty (Q15–Q19), and satisfaction (Q20 and Q21).

Other students in the control group were asked only two categorical questions: technical knowledge before belonging to the mechanical engineering department (Q1', Q3', Q5', and Q6') and at present (Q2', Q4', Q6', and Q8'), and motivation and interest before belonging to the mechanical engineering department (Q9', Q11', and Q13') and at present (Q10', Q12', and Q14'). The questions about before belonging to the mechanical engineering department were dummy questions, with the purpose of comparing students in the attending and the control groups at the same academic times (i.e., first semester of the four years).

The scores were normalized between 0 and 1 in each category. Technical knowledge, motivation, and interest were compared to determine whether these had improved from before using one-tailed Wilcoxon signed-rank tests. To evaluate whether our course improved the scores, we compared the students in the attending and control groups using one-tailed Welch's t-tests.

IV. RESULTS

We evaluated the course based on the results of the questionnaire survey (Fig. 4, right). All students reported that the course improved their technical knowledge score (increase of 0.40 ± 0.18 [mean ± standard deviation]) and the difference was statistically significant ($p = 0.002$), although their initial self-assessment was very low (0.12 ± 0.09) (Fig. 6a). The students were highly motivated by the course (0.69 ± 0.12) (Fig. 6b), and this improved significantly over the course (from 0.12 ± 0.09; $p = 0.002$). We presumed that the difficulty of the course was appropriate for the students. Although they considered the course to be difficult (0.69 ± 0.18), they felt there were no major barriers to using the microcontroller and LRF. The students reported no marked differences between the difficulty of the programming of microcontrollers and desktop computers (the mean score of Q17 was moderate; 0.50 ± 0.17) (Fig. 4, right). Furthermore, this assessment showed a fair degree of satisfaction (0.70 ± 0.21) (Fig. 6c). The course was clearly considered to be beneficial (very high mean Q21 score: 0.92 ± 0.12) (Fig. 4, right), although not all students were satisfied with the quality of their final project (moderate mean Q20 score: 0.47 ± 0.38) (Fig. 4, right).



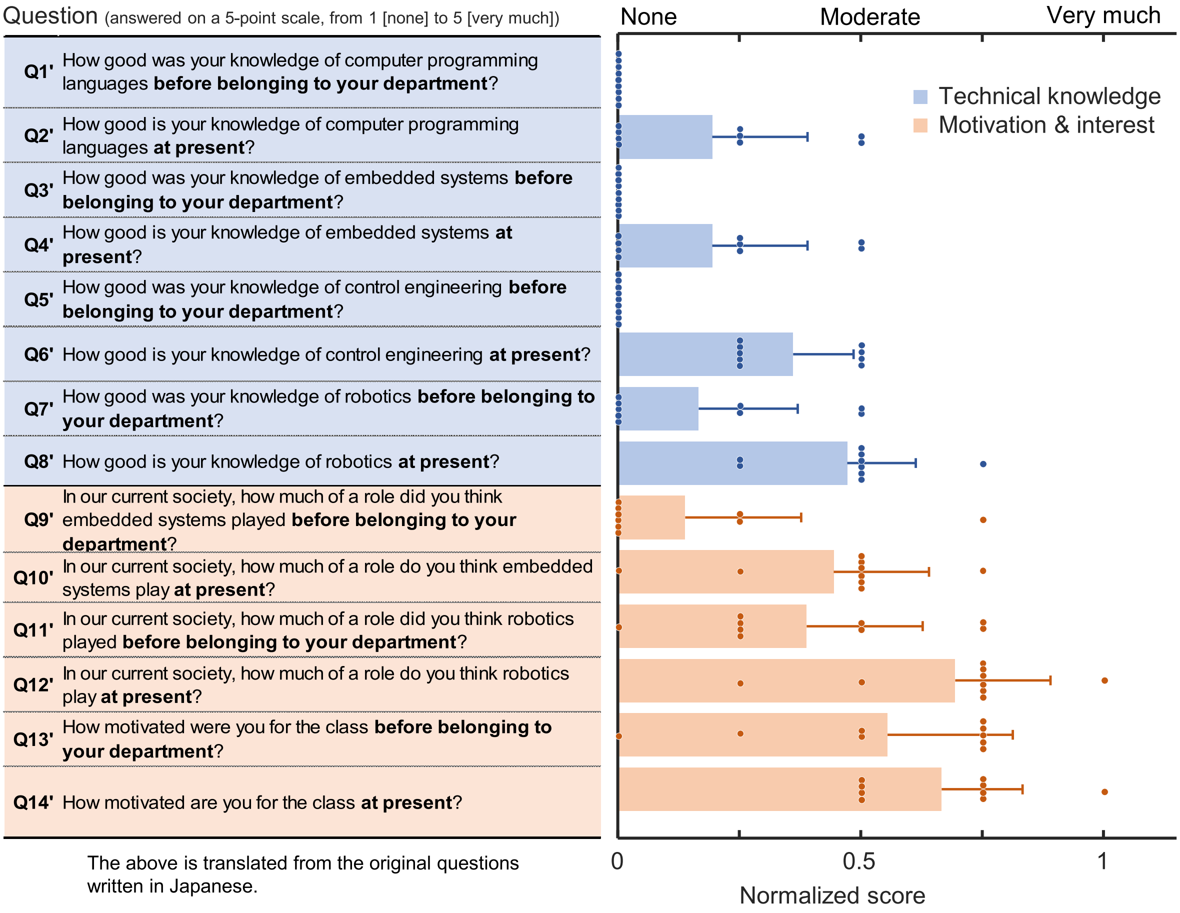
	Question (answered on a 5-point scale, from 1 [none] to 5 [very much])
Q1	How good was your knowledge of computer programming languages **at the beginning of the course**?
Q2	How good is your knowledge of computer programming languages **after the course**?
Q3	How good was your knowledge of embedded systems **at the beginning of the course**?
Q4	How good is your knowledge of embedded systems **after the course**?
Q5	How good was your knowledge of control engineering **at the beginning of the course**?
Q6	How good is your knowledge of control engineering **after the course**?
Q7	How good was your knowledge of robotics **at the beginning of the course**?
Q8	How good is your knowledge of robotics **after the course**?
Q9	In our current society, how much of a role did you think embedded systems played **at the beginning of the course**?
Q10	In our current society, how much of a role do you think embedded systems play **after the course**?
Q11	In our current society, how much of a role did you think robotics played **at the beginning of the course**?
Q12	In our current society, how much of a role do you think robotics play **after the course**?
Q13	How motivated were you for the class **at the beginning of the course**?
Q14	How motivated are you for the class **after the course**?
Q15	How theoretically complicated do you think it is to study using computers and robots?
Q16	How practically complicated do you think it is to study using computers and robots?
Q17	How difficult do you think programming embedded systems is compared to programming desktop computers?
Q18	How theoretically complicated do you think the course is?
Q19	How practically complicated do you think the course is?
Q20	How satisfied are you with the quality of your work for the final project?
Q21	What quantity and quality of knowledge have you acquired from the course?

The above is translated from the original questions written in Japanese.

FIGURE 4. Questionnaire administered to students who attend our course (attending group), and the results. Questions categorized according to the assessment purpose, "technical knowledge," "motivation and interest," "difficulty," and "satisfaction," indicated in blue, red, yellow, and green, respectively. The questions were answered on a 5-point scale, from 1 (none) to 5 (very much), and each answer was normalized to the score from 0 to 1. In right panel, horizontal bars and lines show the mean scores of the participants and the standard deviations (SDs), respectively. Dots show the data of individual participants.

In the control group, the students reported how their technical knowledge, motivation, and interest had improved from when they started, at the beginning of the program steps (Fig. 5, right). All of them indicated significant improvement in "technical knowledge" and in "motivation and interest" at present: 0.31 ± 0.13 from 0.04 ± 0.05 ($p = 0.002$) and 0.60 ± 0.15 from 0.36 ± 0.20 ($p = 0.004$), respectively (Fig. 6d–e).

During same academic periods, the attending group showed higher scores on "technical knowledge" (0.40 ± 0.18) than the control group (0.31 ± 0.13) (Fig. 6a–d). The score for "motivation and interest" (0.69 ± 0.12) was also higher than that of the control group (0.60 ± 0.15) (Fig. 6b–e). However, the differences were not significant but marginally significant (technical knowledge: $p = 0.064$; motivation and interest: $p = 0.086$).



	Question (answered on a 5-point scale, from 1 [none] to 5 [very much])
Q1'	How good was your knowledge of computer programming languages **before belonging to your department**?
Q2'	How good is your knowledge of computer programming languages **at present**?
Q3'	How good was your knowledge of embedded systems **before belonging to your department**?
Q4'	How good is your knowledge of embedded systems **at present**?
Q5'	How good was your knowledge of control engineering **before belonging to your department**?
Q6'	How good is your knowledge of control engineering **at present**?
Q7'	How good was your knowledge of robotics **before belonging to your department**?
Q8'	How good is your knowledge of robotics **at present**?
Q9'	In our current society, how much of a role did you think embedded systems played **before belonging to your department**?
Q10'	In our current society, how much of a role do you think embedded systems play **at present**?
Q11'	In our current society, how much of a role did you think robotics played **before belonging to your department**?
Q12'	In our current society, how much of a role do you think robotics play **at present**?
Q13'	How motivated were you for the class **before belonging to your department**?
Q14'	How motivated are you for the class **at present**?

The above is translated from the original questions written in Japanese.

FIGURE 5. Questionnaire administered to students in the control group to compare students 'before belonging to the department' with the present. The students did not attend our course. The format is same as Fig. 4.

V. DISCUSSION

This paper describes an inexpensive mobile robot for application to STEM education for mechanical engineering students and then outlines the course for the project. We implemented this course in our classes and evaluated it by administering a questionnaire to the students. The students reported that the course improved their knowledge and encouraged their motivation and interest in the technologies of embedded systems and robotics. The students were satisfied with the course program. Although they experienced some difficulty in using the computers and robots, they did not perceive any big difference in programming the robot compared to that required for desktop computers. On the other hand, not all students felt satisfied with the quality of their final project. These findings indicate that the course was appropriate for the students in terms of difficulty. Therefore, our robotics course improved technical knowledge, and motivation and interest, in mechanical engineering students.

It should be noted that, at present, it is difficult to apply Arduino microcontrollers in conjunction with the Hokuyo LRF to simultaneous localization and mapping (SLAM) algorithms, due to the limited processing capacity of the microcontrollers. A commercial mobile robot TurtleBot3 Burger (Robotis, Seoul, Korea) is equipped with several advanced sensors, including an LRF, for a significantly lower price (549 USD). However, it uses the Robot Operating System (ROS) [54], which often requires the use of a command line interface (e.g., shell script or command prompt), which makes it more suitable for higher level students, such as graduate/masters-level students, as opposed to undergraduates [31]. In addition, the ROS has a critical disadvantage of incompatibility, due to its limited adoption in industrial applications, depending on software versions.

Raspberry Pi (Raspberry Pi Foundation, Cambridge, UK) is well known as an inexpensive computer for educational use, similar to the Arduino concept. Raspberry Pi achieves multifunctionality and multitasking, allowing for advanced processing. Thus, Raspberry Pi can be connected to multiple LRFs, including those made by Hokuyo LRFs. However, unlike Arduino, it requires a Linux-based operating system (OS) such as Raspbian, and beginner users must start by learning how to use the OS. Besides, Raspberry Pi has poor compatibility with some electronic components, making it challenging to work with analog circuits. Therefore, Arduino

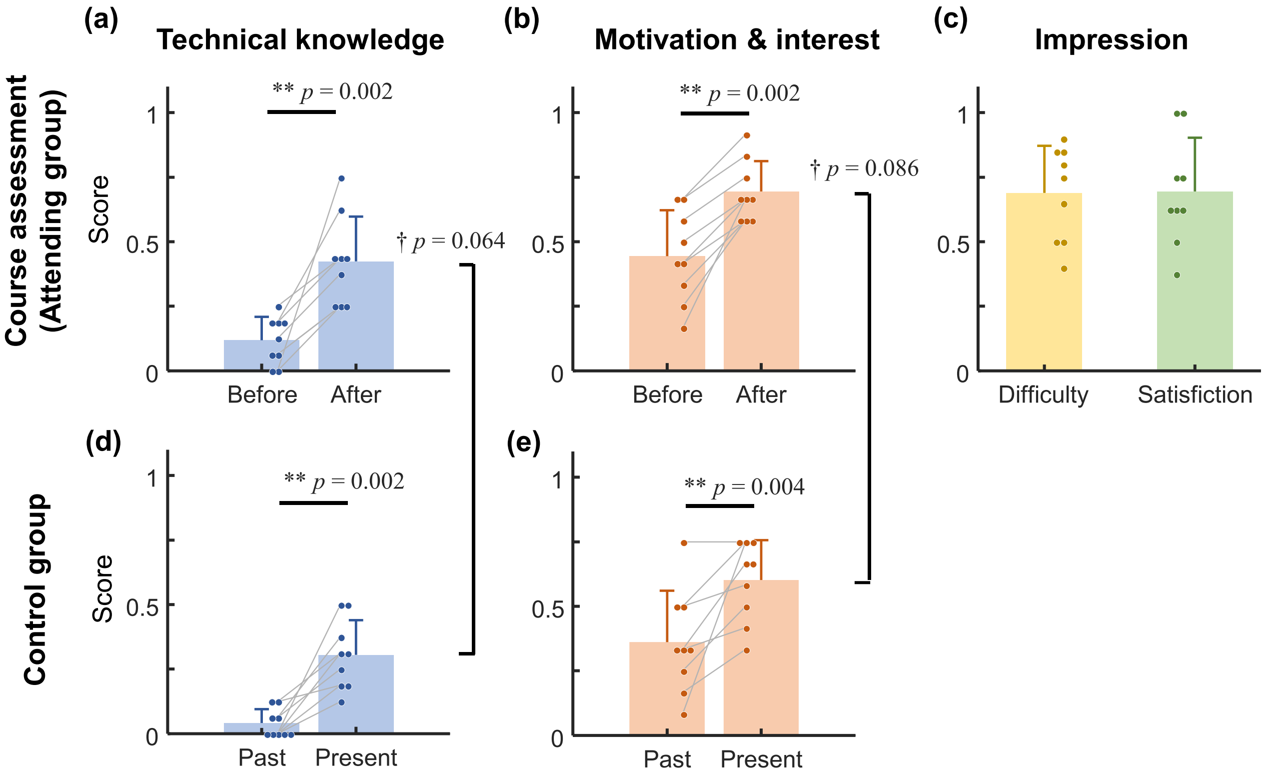


FIGURE 6. Course assessment and comparison with the control group. Dots, gray lines, and vertical lines show the data of individual participants, their changes, and the SDs, respectively. In (a–b, d–e), p-values comparing two components are shown near lines bridging them. (a) Technical knowledge before and after the course. (b) Motivation and interest in relevant technologies before and after the course. (c) Impression of the difficulty and satisfaction with the course. (d) Technical knowledge from the past before belonging to the department and at present. (e) Motivation and interest in relevant technologies in the past before belonging to the department and at present.

is considered suitable for beginners in programming for simple applications such as controlling motors. We believe the best approach for students is to start with Arduino and then move to Raspberry Pi when they are ready for more advanced learning.

In recent years, cheaper LRFs have been produced. To our knowledge, the RPLIDAR-A1 (Shanghai Slamtec, Shanghai, China) is the cheapest LRF, costing only 100 USD. This LRF provides good performance for educational purposes, although its durability is unclear [55]. As the Shanghai Slamtec LRF family uses serial universal asynchronous receiver/transmitter and USB interfaces, it could potentially replace the Hokuyo LRF described in this paper; this would reduce the total system cost to 365 USD, which is lower than the TurtleBot3 Burger.

Some limitations should be noted. First, at present, it is difficult to apply Arduino microcontrollers in conjunction with the Hokuyo LRF for SLAM algorithms, due to the limited processing capacity of the microcontrollers. However, because our robot allows for communication with other devices via a Wi-Fi connection, SLAM could be implemented by cooperating with an external computer.

Second, the study participants were similar in age and gender; thus, the diversity among participants was small. Additionally, they belonged to the same, single school, and the sample size of our survey was small. In this regard, a recent study reported that girls are more likely to have a negative attitude toward mathematics than boys as they grow up during the primary school years [56]. Thus, there may be gender gaps in attitude toward STEM education.

Third, the small sample size was not insufficient for our course assessment according to a post-hoc analysis. The effect sizes were 1.7 at least. The effect size could be computed as the statistical power at 0.998 for the one-tailed Wilcoxon signed-rank test from a statistical power analysis using G* Power [57], under an assumption of a significance level at 0.05, and sample size of 9. The results suggest that the small sample size was not a significant problem regarding evaluation of skill/motivation improvements after taking the course. However, the effect sizes between the attending and control groups were at most 0.76. The statistical power was low at 0.46, computed for the one-tailed Welch's t-test under an assumption of a significance level at 0.05, and the total sample size of 18 (attending group: 9 students; control group: 9 students). This indicates that the sample size was not sufficient for this comparison. A total sample size of 46 (23 students in each group) is required to satisfy the significance level at 0.05, and statistical power of 0.80. Thus, a further survey is required to validate the comparison between the attending and control groups.

VI. CONCLUSION

This paper and the associated online materials discuss how to integrate a Hokuyo LRF with an Arduino microcontroller to build a cost-effective autonomous mobile robot. Application to a STEM education class for mechanical engineering students is also described. We recommend the integration of this LRF and this microcontroller for educational purposes. Our materials can help teachers of mechanical engineering departments to incorporate these devices into their courses, thus helping students to become more enthusiastic about the class and project work. Earlier, we proposed two research questions regarding 1) the ability and cost-effectiveness of integrating Arduino and Hokuyo LRFs to create an educational robot and 2) the educational effects. The first question was solved, with online materials and codes provided for those interested. The second question was addressed in the questionnaire results.

In future work, we will incorporate the SLAM system into the course program. Furthermore, we are developing another theme for the project work. It is planned as a swarm control application that integrates robots of multiple units with a motion capture system.

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AUTHOR CONTRIBUTIONS

Yuki Ueyama designed and prepared the materials, practiced the curriculum, collected and analyzed the data, and wrote the manuscript. Takashi Sago, Toru Kurihara, and Masanori Harada supported practicing the classes. All authors approved the final manuscript.

SUPPLIMENTARY MATERIAL

The supplementary material includes videos (S1.mp4, S2.mp4).

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