Smart Learning Environments

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Exploring the efficacy of collaborative learning in a remote robotics laboratory: a comparative analysis of performance and pedagogical approaches

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Abstract

In today's world, remote-controlled robots are widely used across various industries due to their ability to enhance working efficiency in various applications. Learning about robot operation and human–computer interaction has emerged as a popular topic in recent times. Indeed, learning robotics can be challenging for many students as it requires knowledge of programming, control systems, electronics, etc. Collaborative learning in a physical robotics setting is common in higher education and has received significant attention for its potential to enhance individual learning outcomes. However, the effectiveness of learning robotics in a remote setting is still a matter of debate. In this study, we establish a remote laboratory environment to teach undergraduate students in the engineering discipline. Students are required to utilize a robotic arm to grasp designated objects collaboratively among students through synchronous interactions online. To compare students' performance under different pedagogical teaching approaches, students are divided into two groups. They each perform the task individually and collaboratively, albeit in a different order. Our study adopts a quantitative method to measure students' learning outcomes based on the assessment of performing the laboratory tasks and completion time. The results indicate a noteworthy improvement in the individual performance of the group of students who engage in collaborative work prior to the individual tasks. These findings have implications for other remote laboratory setups and highlight the effectiveness of collaborative learning in higher education.

Keywords: Remote laboratory, Collaborative learning, Robotics, Human–computer interaction

Introduction

In this era of information and technological advancements, the widespread use of the internet and new technologies has enabled remote teaching and learning, breaking down geographical barriers. The rapid growth of digital transformation has brought about unprecedented changes in our daily lives. Through the utilization of virtual technologies and human–computer interaction, educators and students can now connect remotely to schools and laboratories, overcoming challenges such as social distancing, the need for international learning, and synchronous learning approaches (Godber & Atkins, 2021; Osorio-Saez et al., 2021). As a result, educational institutions have swiftly transitioned to emergency remote teaching and learning, leading to accelerated adoption of mobile devices (Tang et al., 2021) and video conferencing software like Zoom for remote education (Agusriadi et al., 2021; Dias et al., 2020). Coupled with the vast resources available on online platforms, this shift from traditional physical classrooms to remote teaching and learning has positively revolutionized global education, granting students access to education regardless of their physical location.

During the pandemic, remote learning approaches have gained significant traction in supporting teaching and learning for students. However, there remains a dearth of research on the application of remote collaborative learning in practical subjects. Specifically, limited attention has been given to studying students' teamwork and collaboration during remote learning, as well as the pedagogical approaches employed in remote teaching. Moreover, there is a noticeable lack of research that compares collaborative and individual learning in the context of remote education. Specifically, the exploration of how collaborative-supported teaching can benefit students' individual studies in the domain of robot training is lacking. Consequently, the research questions surrounding the effective pedagogical approach for remote collaborative teaching in practical subjects have yet to be comprehensively addressed. Addressing these research questions contribute to the development of comprehensive frameworks and guidelines that enhance the effectiveness of remote collaborative learning in practical subjects.

Therefore, the scientific aim of this work is to explore the effectiveness of remote collaborative teaching and develop an effective pedagogical approach to student learning. The research focuses on obtaining quantitative data based on individual learning performance to support our findings. This study extends existing research by enhancing our understanding of pedagogical teaching design in the context of remote collaborative teaching. It offers insights into pedagogical approaches for conducting remote learning through collaborative teaching of robotics and programming to university students. These insights can inform the design of future remote learning experiences.

Literature review

Collaborative learning

Remote collaborative learning has gained significant attention in educational research as a promising approach to enhancing individual learning outcomes (de Nooijer et al., 2021; Gopinathan et al., 2022). Remote collaborative activities, such as group projects, case studies, and discussions, can be facilitated through online platforms, fostering engagement and active learning. However, this collaborative approach may not be practical for subjects that require hands-on skills and practical knowledge. Many existing approaches utilize online learning management systems for teaching, assessment, and student management (Mo et al., 2022). Nonetheless, limited research has explored the application of remote collaborative learning in practical subjects. For example, Cheung et al. (2023) explored the use of VR models to aid students in acquiring vaginal examination skills. Nonetheless, the hands-on skill components are still delivered in person, allowing students the flexibility to acquire the necessary vaginal examination skills using VR devices if needed. Despite the valuable e-learning experiences provided, laboratory sessions remain an essential and irreplaceable component in science and engineering disciplines. Laboratories serve the purpose of challenging students to apply the theoretical concepts they have learned, including abstract theorems, to practical scenarios (Wilkerson et al., 2022). Practical learning is invaluable for students in the science and engineering fields as it provides authentic learning experiences and teaches valuable skills (Gya & Bjune, 2021; Su & Chen, 2023). Surprisingly, not much research has been conducted on the application of remote collaborative learning in practical subjects. Svatos et al. (2022) conducted online teaching of practical classes where students were required to design GUIs and perform programming exercises. However, the studies only reported on the remote laboratory practice of students, without investigating the team working and collaboration among students or the pedagogical teaching method.

Remote learning technologies

Remote collaborative learning using robotics is another alternative, with recent studies highlighting the benefits of remote access to robotic systems and collaborative learning strategies in improving students' understanding and skills in robotics (Rosenberg-Kima et al., 2020). For example, Zhang et al. (2020) found that collaborative learning in a remote robotic laboratory setting led to improved individual performance and increased engagement among students. Similarly, (Osorio-Saez et al., 2021) reported that remote collaborative learning activities involving robotic experiments resulted in enhanced problem-solving abilities and critical thinking skills in individual learners. These findings underscore the positive impact of remote collaborative robotic learning on individual learning outcomes, highlighting its potential as an effective pedagogical approach.

While different methodologies have been proposed for remote laboratories, facilitating collaborative learning and active student engagement remains a challenge in remote learning. Collaboration among students has been achieved through approaches such as web-based platforms (Roehrig & Bischoff, 2004; Tang et al., 2022), virtual and mixed reality (Schaf et al., 2009; Wu et al., 2021), software platforms with communication tools (Bochicchio & Longo, 2010; Herrera & Fuller, 2011; Jara et al., 2012; Odeh & Ketaneh, 2012), and video conferencing software (de la Torre et al., 2013). Pang et al. (2022) investigated students' perceptions of remote labs for robotics courses using a questionnaire. However, there is a lack of research comparing the differences between collaborative and individual learning and exploring how collaborative-supported teaching can benefit students' individual studies in robot training.

Methodology

In this section, we present the methodology employed in our study, which is divided into three subsections. "Key learning objectives" section focuses on the key learning objectives that were established for the research. These objectives served as the foundation for designing and implementing the remote collaborative learning laboratory, which is described in "Laboratory setup and task" section. The setup of the laboratory, including the technological infrastructure and tools used, is elaborated upon. Finally, "Assessment method" section outlines the evaluation method employed to assess the effectiveness of the remote collaborative learning approach. This section provides an overview of how the data were collected and analyzed to measure the achievement of learning outcomes.

Key learning objectives

In this laboratory, our main emphasis is on instructing students in the operations of robotic arms. The laboratory aims to offer students a practical understanding of using a robotic arm to effectively grip a designated object. This laboratory encompasses various significant learning objectives for students, which include gaining comprehension of robotics principles, cultivating programming abilities, fostering collaborative problem-solving skills, developing applied engineering skills, acquiring practical hands-on experience, enhancing communication and teamwork capabilities, as well as fostering analytical thinking and problem-solving aptitude.

Students learn the foundational concepts and principles behind robotics, including kinematics, dynamics, and control systems. They gain proficiency in programming the microcontroller for motion control, path planning, and task execution. They have the opportunity to work effectively in teams, collaborating with their peers to solve complex problems and complete tasks using the robotic arm, thereby enhancing their communication and teamwork skills through effective collaboration, idea sharing, and coordinated efforts to achieve common goals.

Through practical remote collaboration, students gain valuable practical experience, allowing them to develop essential technical skills. They apply their knowledge of engineering principles to design and execute tasks, demonstrating their ability to apply theoretical concepts to real-world applications. Additionally, students develop their analytical thinking abilities by analyzing problems, identifying potential solutions, and implementing strategies to overcome challenges encountered during remote collaborative robotic tasks.

The details assessment on evaluating whether the learning objectives can be achieved are described in "Assessment method" section.

Laboratory setup and task

In order to facilitate student participation in remote collaborative robotics laboratories, a setup for remote collaborative learning is developed. This setup consists of several essential components, such as a control computer, a hosting computer, a microcontroller board, a camera, and a robotic arm. Additionally, a teaching assistant is present to guide students through the fundamental operations of the remote collaborative laboratory, as well as to provide instruction on the key concepts and learning objectives of the lab. Figure 1 shows the overview of the remote collaborative laboratory.

After students learnt the fundamental operations and programming skills, they are required to develop a graphical user interface (GUI) to control the robotic arm using Arduino and MATLAB to complete the teaching and learning task. Arduino is an open-source single-board microcontrollers and microcontroller kits for building digital devices. The Tinkerkit Braccio, shown in Fig. 2, is a fully operational robotic arm, controlled via Arduino. It can be assembled in several ways for multiple tasks such as moving objects. The braccio has a total of six joints with the corresponding digital motor range given in Table 1. On the other hand, MATLAB is a proprietary

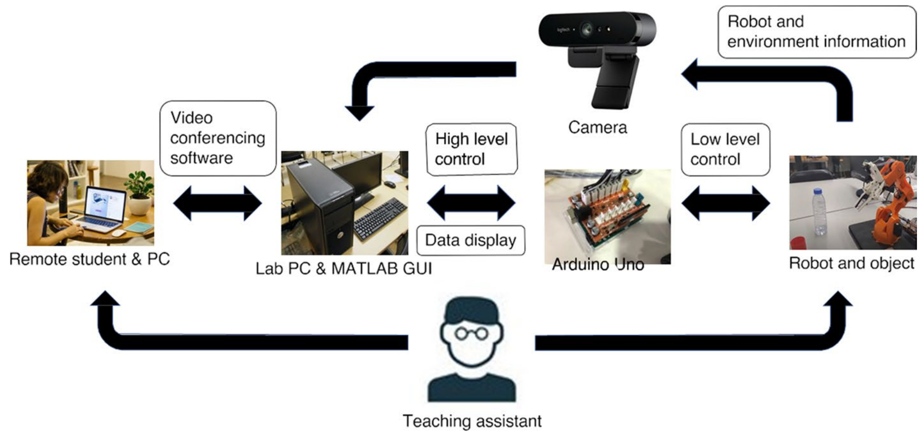

Fig. 1 Overview of the remote collaborative laboratory setup

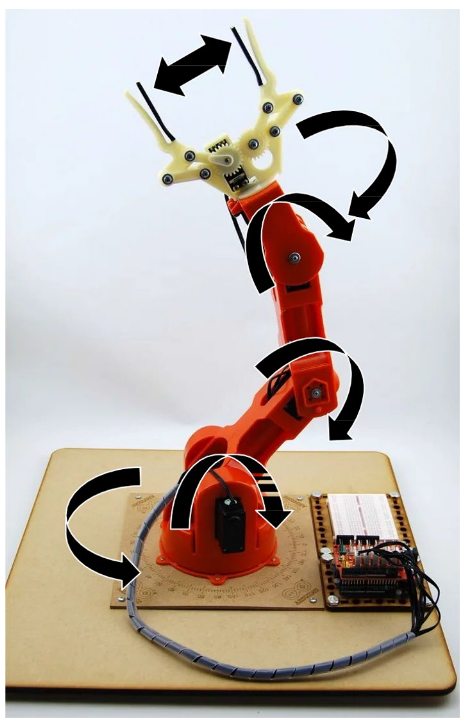

Fig. 2 The Tinkerkit Braccio Robot used in the remote collaborative laboratory. It has six joints with their digital motor range illustrated by the arrows

Table 1 The joints and the corresponding digital motor range of the Tinkerkit Braccio Robot

Number	Joint	Digital motor range
1	Base	[0, 180]
2	Shoulder	[15, 165]
3	Elbow	[0, 180]
4	Wrist vertical	[0, 180]
5	Wrist rotation	[0, 180]
6	Gripper	[10, 73]

multi-paradigm programming language and numeric computing environment developed by MathWorks. It is the industry standard in engineering discipline and students will be benefit from having programming experience in it. The laboratory is setup in a remote manner that the activities in person have been substituted by remote connection with camera, where collaboration between students can be achieved through synchronous interactions using the video conferencing software, and data collection is allowed even the students are not physically in the laboratory.

To initiate the tasks, students are instructed to set up a remote collaborative learning environment. This requires a computer with an internet connection, camera, and video conferencing software using Microsoft Teams. The first step for students is to sign in to the video conferencing software in order to establish a connection between their remote computer and the laboratory's computer. Once the connection is established, students can access the necessary software on the laboratory's computer. Next, students need to connect the Arduino board through the laboratory's computer. This will enable communication between the Arduino and MATLAB, which is essential for the completion of the following tasks. Additionally, students need to prepare the MATLAB workspace through the laboratory's computer.

Once the learning environment has been set up, the control graphical user interface (GUI) design in MATLAB is taught by the instructor. Students are required to learn how to develop the control GUI design, establish communication between the robotic arm and MATLAB, and set up the display module. The basic components of the GUI, such as push buttons, edit text boxes, static text boxes, and sliders, are introduced. Students are also required to learn how to place the GUI components on the MATLAB canvas. In the second step, the attributes of the components are modified by the students. In the third step, the callback function of each component is found and edited by the students. Finally, in the last step, the students learn how to run their code and generate an interactive window. Figure 3 shows an example of the GUI that students are required to develop for the control of the robotic arm.

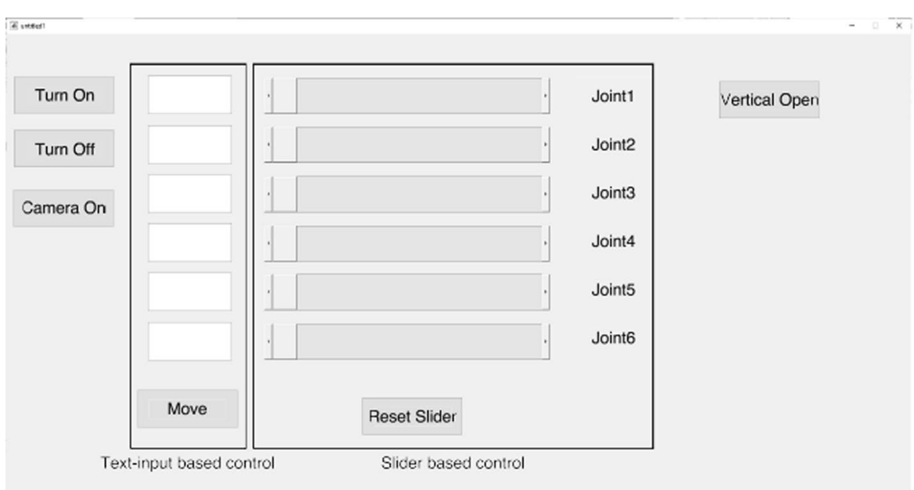

Fig. 3 The example of the GUI which students are required to develop for the control of the robotic arm

To establish the connection between the robotic arm and MATLAB, students need to create two push buttons. The first button, labeled "TurnOn," is used to set up the connection between MATLAB and the Arduino. The second button, labeled "TurnOff," is used to shut down the connection. The display module captures the movement of the robotic arm. To set up the display module, students need to create a push button labeled "CamOn" that activates the cameras. By clicking the "CamOn" button in the "Run" mode, a window displaying the camera's content appears. After completing the above preparation work, students should be able to remotely develop a GUI for controlling robotic arms in MATLAB, establish communication between MATLAB and the Arduino for interacting with the robotic arm, and observe the movement of the robotic arm through the camera.

Assessment method

A robotics course is selected for evaluation. All the participating students in this study are undergraduate students with a similar educational background, possessing fundamental knowledge in electronics, programming, information technology, and engineering mathematics. To perform the experiments, students are first randomly separated into two groups. In the first group, students are organized into teams of three members who collaborate to complete a specific task. In the second group, students are required to individually complete a specific task. The tasks assigned to the students are accompanied by several key assessment measures that are recorded during the experiments. At the beginning of both laboratory sessions, students receive instruction on the key concepts related to robotic arms and foundational programming skills. Throughout the sessions, students are required to work together or individually to successfully control the robotic arm and grasp a targeted object. One hour is allocated for students to practice in the laboratory.

Upon completing the first task, students are given approximately one week to reflect on what they have learned. Subsequently, another task of the same level of difficulty is assigned to the students. In this second task, the students who previously worked collaboratively in the first task are now required to work individually, while the students who initially worked individually are organized into teams of three members for collaborative learning. The allotted time for completing both tasks was set at 90 min.

The student's performance was evaluated by running the laboratory tasks. To minimize bias, three markers carried out the evaluation process independently, and the average rating was calculated for each metric. The marker evaluates the performance using a 5-point Likert scale ranging from poor to excellent based on the quality of the students works. The laboratory tasks are intended to assess student's ability in achieving the learning outcomes in integrate and apply knowledge, carry out laboratory procedures, adhere to instructions, and logical trouble shooting. The assessment focus on four metrics in GUI complexity, remote control performance, robot performance, and time spent on task completion. The quality and completeness of the tasks, including meeting all requirements and achieving the objectives. The time taken to complete the tasks was measured in minutes, with a lower number indicating a better rating.

Results

Data

In this study, a total of 45 students participated as participants. Among the participants, there was a nearly equal distribution of gender, with 48.9% being male and 51.1% being female. Out of the total participants, 23 students were assigned to groups for the purpose of conducting remote collaborative learning as the initial task. Additionally, 48.9% of the students started the learning process individually before engaging in collaborative activities (Table 2).

Normality tests

To ensure the validity of the subsequent statistical analysis, normality tests were conducted to examine the assumption of normality in the data. Prior to testing our hypothesis, we performed a normality test on the students' performance (Hair et al., 2019). This test evaluates the shape of the distribution by calculating the skewness and kurtosis. The skewness and kurtosis of the distribution is used for normality test as it is relatively correct in both small samples and large samples (Kim, 2013). Skewness measures the symmetry of the distribution in relation to a normal distribution. A positive value indicates a right-tailed distribution, while a negative value indicates a left-tailed distribution. Skewness values outside the range of -1 and + 1 indicate a significantly skewed distribution. Kurtosis, on the other hand, measures the peakedness or flatness of the distribution compared to a normal distribution. A positive value suggests a relatively peaked distribution (leptokurtic) and a negative value suggests a relatively flat distribution (platykurtic). In line with Fisher's definition, the kurtosis of a normal distribution is 0.

Furthermore, a statistical test is utilized to assess the normality assumption. The test statistic for skewness is calculated based on the skewness and kurtosis values, and it is used as an additional measure for evaluating normality. The statistic value for the skewness is calculated in Eq. (1) as,

$$Z_{skewness} = \frac{skewness}{\sqrt{6/N}} \tag{1}$$

where N is the sample size, and the statistic value for the kurtosis is calculated in Eq. (2) as,

$$Z_{kurtosis} = \frac{kurtosis}{\sqrt{24/N}} \tag{2}$$

Table 2 The demographic information of the participants

	Details	Number (%)
Gender	Male	22 (48.9%)
	Female	23 (51.1%)
Tests	Collaboration first	23 (51.1%)
	Individual first	22 (48.9%)
Total		45

Table 3. The skewness, kurtosis, and the corresponding statistic value *z* for the distribution of the student's individual performance who worked individually followed by collaborative tasks

	Skewness	Kurtosis	$Z_{skewness}$	$Z_{kurtosis}$
GUI complexity	0.390220	0.571082	0.747214	0.546769
Remote control performance	0.619582	− 0.079373	1.186408	− 0.075994
Robot performance	0.285963	− 0.541897	0.547578	− 0.518827
Time cost	0.067470	− 1.609144	0.129196	− 1.540638

Table 4 The skewness, kurtosis, and the corresponding statistic value *z* for the distribution of the student's individual performance who worked collaboratively followed by individual tasks

	Skewness	Kurtosis	$Z_{skewness}$	$Z_{kurtosis}$
GUI complexity	− 0.703451	− 0.152552	− 1.377279	− 0.149340
Remote control performance	− 0.430088	0.083721	− 0.842065	0.081959
Robot performance	− 0.590007	− 0.366213	− 1.155169	− 0.358503
Time cost	1.474269	1.997488	2.886456	1.955431

If the calculated z-value exceeds the specified critical value, which is ± 1.96 for small samples with $N < 50$ at a significance level of 0.05, it indicates that the distribution is non-normal in terms of that characteristic. The students' performances on four metrics in GUI complexity, remote control performance, robot performance, and time spent on task completion for both individual and collaborative work scenarios are presented in Tables 3 and 4. Based on Table 3, all the z-values fall within the range of ± 1.96, indicating a normal distribution. In most cases, the z-values in Table 4 also fall within the ± 1.96 range, except for the z-skewness values for time cost and the z-skewness value for time cost in Table 4. The z-skewness values in Table 3 are all positive, suggesting a right-tailed distribution. Moreover, the statistic value for the kurtosis is mostly negative, which implies a leptokurtic distribution. Based on these findings, we assume that the students' performances are approximately normally distributed and can be analyzed using the student's t-distribution.

Statistical analysis

In this section, we employed descriptive and statistical analysis to assess the performance of students in four assessment metrics, comparing the students perform tasks individually and collaboratively first. Additionally, we examined the significance of mean differences using a 95% confidence interval. A p-value less than 0.05 was considered statistically significant, while a p-value greater than 0.05 was not.

Descriptive statistics were used to visually represent the results using boxplots, providing information about the distribution and skewness of numerical data. To determine the statistical significance of the difference between two sample means for a single dependent variable, we checked if the student data followed a t-distribution. Subsequently, we utilized the paired sample t-test to calculate the statistical significance.

Figure 4 displays the descriptive results through boxplots, showcasing the mean values for the assessment metrics and the time taken to complete the tasks. Upon initial

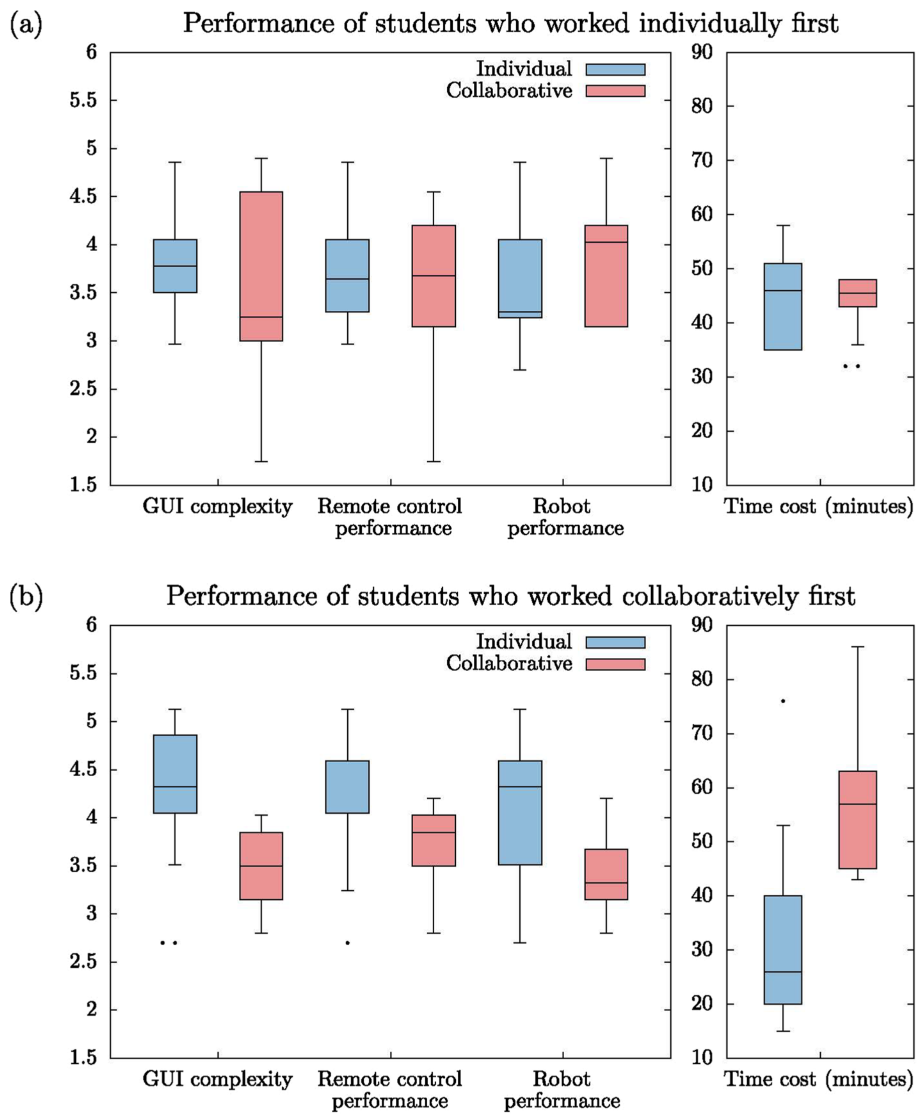

Fig. 4 Boxplots for the performance of students worked **a** individually first, and **b** collaboratively first

observation, there appears to be no significant difference in individual or collaborative performance for students who worked individually followed by collaborative tasks. However, a significant improvement in individual performance is observed for students who worked collaboratively followed by individual tasks. The results indicate that the mean scores across the measurement metrics are similar. However, in the case of individual tasks completed first, the students exhibit a wider range of scores compared to the students who performed collaborative tasks first. Conversely, when collaborative tasks were completed first, the students display higher mean scores in all metrics compared to the students who performed individual tasks first. Additionally, the time taken to complete the tasks is shorter.

Statistical analysis was then performed to compare the significance of the measurements between the students who performed individual and collaborative tasks first. The results are presented in Table 5. It is observed that only the robot performance exhibits statistical significance, indicating a small improvement in robot performance when students worked collaboratively after working individually. However, the other assessment measures do not show significant differences. On the other hand, the results demonstrate that all differences between the paired sample means are statistically significant, leading to the rejection of the null hypothesis. Consequently, we conclude that collaboration between students results in improved individual performance across all aspects. Based on these findings, we conclude that collaboration between students leads to improved individual performance and better learning outcomes.

Discussion

Based on the findings presented above, it can be concluded that collaboration between students has a positive impact on individual performance and overall learning outcomes in terms of GUI design, remote control, robot performance, as well as the time required for completing the tasks. When comparing the students performed tasks individually and collaboratively first, the results showed that students who engaged in collaborative tasks first exhibited higher mean scores in all assessment metrics compared to the students performing individual tasks first. Additionally, the time taken to complete the tasks was shorter. These findings align with previous research that highlights the benefits of collaborative learning (Johnson & Johnson, 2015; Slavin, 2014). Collaborative learning involves students working together in groups, actively engaging in discussions, sharing ideas, and solving problems collectively. This approach has been shown to enhance critical thinking skills, promote deeper understanding of concepts, and improve academic achievement. This can be reflected through a higher score in the GUI complexity that requires students critical thinking and creativity. The results agree with previous studies on a better co-design process through collaboration (Hu et al., 2022; Wong et al., 2021).

On the other hand, the observed improvement in individual performance when students worked collaboratively first can be attributed to several factors. Collaborative learning provides opportunities for students to actively participate in the learning process, engage in meaningful interactions with their peers, and receive immediate feedback. This can be revealed through a better performance in remote control metric. The results also supported by the previous related articles (Okolie et al., 2021). These interactive experiences foster a deeper understanding of the subject matter and promote higher levels of engagement and motivation (Baanqud et al., 2020). Thus, collaboration

Table 5 Statistical significance for the student's performance in four metrics who worked individually and collaboratively first based on the pair t-test

	p-value	
	Individual first	**Collaboration first**
GUI complexity	0.257779	0.000563**
Remote control performance	0.494291	0.000837**
Robot performance	0.044623*	0.001355**
Time cost	0.624731	0.000002**

*$p < 0.05$; **$p < 0.01$

enhances individual performance by developing critical thinking skills and a necessary understanding of underlying concepts and theories. The results also indicated that the students which completed individual tasks first, exhibited a wider range of scores compared to the students performed collaborative tasks first. This suggests that collaborative learning may contribute to a more consistent and standardized level of performance among students. This agree with the consistent positive effect of collaborative learning demonstrated in Courtney et al. (2022).

Collaborative tasks often involve social negotiation and the integration of diverse perspectives, leading to a more comprehensive and well-rounded understanding of the material (Roseth et al., 2008). However, it is worth noting that the statistical analysis revealed that only the robot performance metric exhibited statistical significance, indicating a small improvement when students worked collaboratively after working individually. This finding suggests that the benefits of collaboration may vary across different assessment measures. Further research is needed to explore the specific factors influencing the impact of collaboration on different aspects of student performance.

The findings from this study provide empirical evidence supporting the effectiveness of collaborative learning in improving individual performance and enhancing learning outcomes. Incorporating collaborative learning strategies in educational settings can create a more dynamic and engaging learning environment, fostering critical thinking, problem-solving skills, and promoting active student participation. The study underscores the importance of student engagement and highlights the benefits of collaborative learning, encouraging educators to integrate these approaches into their teaching methodologies. By doing so, they can create inclusive learning environments where students actively contribute to their own learning and benefit from the diverse perspectives and expertise of their peers.

Furthermore, future research can build upon this study by investigating additional factors that may influence the effectiveness of collaborative learning in remote laboratory settings. These factors include students' personal attitudes and perceptions, the impact of group composition, task complexity, and the role of the instructor. Exploring the correlations between personal attitudes or other factors and students' results would provide valuable insights for optimizing remote collaborative learning experiences. Understanding how these factors contribute to the refinement and improvement of remote laboratory designs and pedagogical approaches can ultimately enhance the quality of education in engineering and related fields.

Conclusion

In this study, a remote laboratory was implemented to teach undergraduate engineering students the fundamentals of robotics and programming. The laboratory simulated a realistic problem-solving scenario using a robotic arm to grasp an object. The study aimed to investigate the impact of effective pedagogical approaches, specifically collaborative learning facilitated by synchronous interactions, on students' learning outcomes. Two groups of students were compared, and the results showed that collaborative learning led to improved individual performance in all aspects of the laboratory experiment.

The study's quantitative and empirical findings have important implications for the development of remote laboratory setups and understanding the effectiveness of collaborative learning in higher education. These results can guide educators and instructional designers in designing and implementing remote collaborative learning environments. By incorporating collaborative learning strategies in remote laboratories, educators can enhance student engagement, promote active learning, and improve learning outcomes across different disciplines, including engineering and robotics.

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Author contributions
Material preparation and data collection were performed by Long Teng. The first draft of the manuscript was written by Yuk Ming Tang and Raymond PH Wu. Gary CP Tsui and Yung Po Tsang contributed to the study's conception and design. CY Tang formulated the research goals and supervision.

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Availability of data and material
The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest
The author(s) declare(s) that they have no competing interests.

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