RobotAR: An Augmented Reality Compatible Teleconsulting Robotics Toolkit for Augmented Makerspace Experiences

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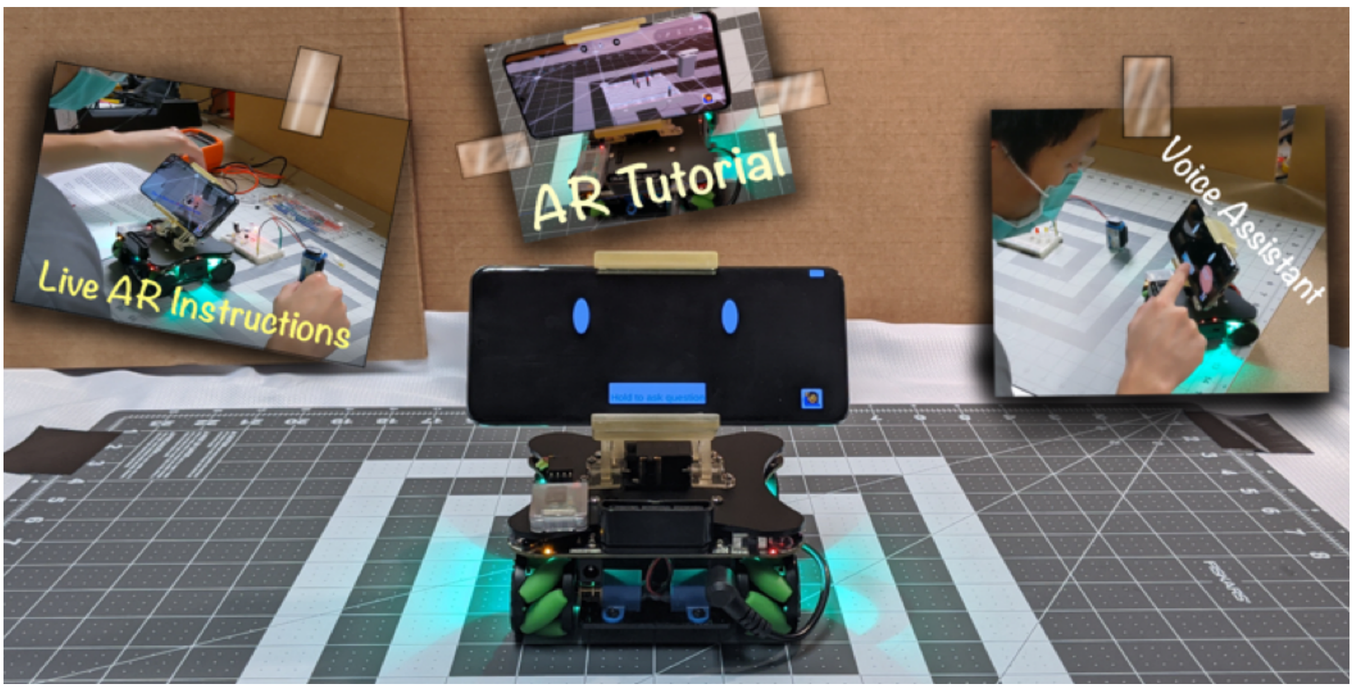

Figure 1: RobotAR is a versatile desktop robot which can make distance learning efficient and enjoyable. It can deliver online instructions, display AR tutorial, and provide voice assistance.

ABSTRACT

Distance learning is facing a critical moment finding a balance between high quality education for remote students and engaging them in hands-on learning. This is particularly relevant for project-based classrooms and makerspaces, which typically require extensive trouble-shooting and example demonstrations from instructors. We present RobotAR, a teleconsulting robotics toolkit for creating Augmented Reality (AR) makerspaces. We present the hardware and software for an AR-compatible robot, which behaves as a student's voice assistant and can be embodied by the instructor for teleconsultation. As a desktop-based teleconsulting agent, the instructor has control of the robot's joints and position to better

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focus on areas of interest inside the workspace. Similarly, the instructor has access to the student's virtual environment and the capability to create AR content to aid the student with problem-solving. We also performed a user study which compares current techniques for distance hands-on learning and an implementation of our toolkit.

CCS CONCEPTS

• **Human-centered computing → Human computer interaction (HCI)**; *Interactive systems and tools*; User interface toolkits.

KEYWORDS

robot; robotics; teleconsulting; voice; augmented reality; makerspaces

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1 INTRODUCTION

Over the past months, teachers, parents, and students witnessed a sudden transition from classroom to home-based learning. This transition highlighted many deficiencies and issues with distance education. Project-based classes and makerspaces had to be cancelled or delivered to students via teleconferencing (e.g., Zoom, Webex, Skype). However, unlike the format of a regular university lecture, hands-on lessons typically require instructor intervention, support, and troubleshooting. In particular, distance education requires the tools to facilitate immersive, hands-on learning without the constraints of geographical bounds. In terms of physical embodiment at a distance, social robots as tutoring agents have demonstrated great potential at achieving learning outcomes in education [51], as well as providing students with access to consulting with the instructor in their own home environment.

In present times, the majority of formerly in-person classrooms have made use of online platforms, such as Zoom [16], Webex [14], Google Classroom [6], Skype [13]. These virtual platforms can offer some of the real-time capabilities as robots-for-tutoring without the cost of hardware, the concern for scalability, and the challenge of installation time; thus, the use of a robot for a distant educational setting needs to be clearly justified.

When comparing a robotics toolkit with an alternate virtual platform or agent, there are three major uses: (a) as tools for curricula and for students who require hands-on engagement with the physical world; (b) as physical embodiments which prompt students to display social behaviors which are conducive to learning; (c) as physical agents which provide interactions that have proven to increase learning gains as compared to virtual agents [24]. Similarly, past work has demonstrated that physical embodied tutoring agents provide an increase on compliance [20, 21, 34], engagement [49, 63], and conformity [44], which in turn provide an increase in cognitive learning gains [52].

Obviously, a robotic system cannot supplement the social in-person aspect of a classroom or the advantage of having an instructor standing next to a student and helping them with problem-solving. However, we can take advantage of new technologies, such as augmented reality (AR)–which overlays virtual information into the physical world [19]–to make use of the virtual world and superimpose instructions, hints, and visual cues into a student's workspace. AR also allows instructors to embody and immerse themselves onto the physical environment. In this paper, we refer to makerspaces with AR superimposed on them as augmented makerspaces. Thus, to address all the previous issues with distance learning at home, we design, prototype, and test RobotAR, and provide the following contributions:

1. An approach for effective teleconsulting desktop-based robots in augmented makerspaces by enabling mobility and translational joints from the robot to better focus on areas of interest inside the workspace.

2. A toolkit for creating augmented makerspaces experiences using an AR-compatible robot that behaves as a tutor to the students, and as a versatile agent with access to the physical and the virtual world during teleconsultation.

3. A user study which compares current techniques for distance learning vs. an implementation of our toolkit.

Aside from our contributions, we will investigate into the effects of our system implementation into a distant makerspace environment. Our work is targeted towards undergraduate students who seek a makerspace-based instruction to mix creativity and technology learning. While we hypothesize that physical embodiment will result in an increase in student engagement [49]; more importantly, we raise another question: *Q1: To what extent does the use of RobotAR lead to an improvement in students' key competencies and user experiences.* If our robotic system allows learners to meet key competences, we ask another question from the point of view of the instructor: *Q2: To what extent does the use of RobotAR allow the instructor to offer more on-point instruction and at a higher level during problem-solving?.* Finally, if both questions result favorably, we wonder how an improvement in learning can influence in the interactions between instructors and students, in the form of the following question: *Q3: To what the extent does the use of RobotAR increase instructor's management and presence in the workspace and promote students' engagement and interest?.* Our work will explore all these research questions. This paper aims to advance our understanding of hands-on distance learning, which is becoming increasingly important in today's society.

2 RELATED WORK

2.1 Social Robots for Education

Social robots are physical agents that interact with humans by following social roles and behaviors attached to those roles [32]. Social robots for education are intended for delivery of learning experiences through *social interactions* with the students. In this context, robots for education have been mainly used in three areas: (a) language acquisition and development, (b) science and mathematics education, and (c) technology and computer programming [66].

Past work has demonstrated the benefits of using a robot in the classroom. Perhaps the most common use of an educational robot has been robot tutoring [23, 45] for teaching a second language [25]. Robot tutoring for second language acquisition, has shown cognitive gains among children, through storytelling and adaption of the robot to the child's knowledge level [46–48, 71].

Robotics for science and mathematics have included gaming using adaptive exercises [43] and teaching equations with the robot addressing an entire group of learners [42]. Technical education with robots typically uses the robot as the learning tool, instead of tutoring [38, 58]. These lesson plans involve introduction to programming the robot and hands-on activities that lead to tinkering and making the robot work [22, 31, 58]. Some of the most commonly used commercial robots adapted for educational interventions have been: NAO [9], RoboThespian [12], Bioloid [3], BAXTER [2], Darwin [4], TIRO [11], Keepon [7], LEGO Mindstorms NXT [41].

The robot as a tutor can provide learning support through multiple hints, visual cues, tutorials, and help with troubleshooting problems. In some cases, the robot is used as the medium to deliver the lesson to the class. Thus, the interactions between the robot and the students are limited and meant to capture the students' attention and encourage engagement with the subject [18]. The robot typically delivers the lesson from one to many students [50, 72]. However, the most frequently used tutoring robots for education allow to teach students individually, in which learning outcomes are highly dependent on the interactions between the robot and the student [65]. The problems with using robot as an individual tutor in the previously mentioned work, include the lack of scalability, portability, and cost. In our work, our toolkit provides a minimalist design that keeps the cost low and allows for easy installation. Similarly, the autonomous aspect of the robot will solve the scalability issue by allowing an individual experience with the robot, open to improvement.

2.2 Teleconsulting and Telepresence Robots

While social robots are used for physical interactions and communication, telepresence robots are embodied agents that enable the user to videoconference while on a moving platform from a distant location [32]. The user has remote control of the mobility and behavior of the robot, and communicates by using the robot as a delivery medium. Telepresence has been used to promote engagement and provide immersion to participants regardless of distance [67].

While the use of telepresence robots has been mainly used in the context of bringing distance students into a physical classroom, teleconsulting robots can be used to bring the instructor into the student's workspace [34]. New technologies (e.g., robotics, AR) can expand the consultation experience for students and make it easier for instructors to diagnose the problem. The benefits of using teleconsultation range from an increase in support and mentoring from the consultant to the consultee [28], an increase in access to rural youth [26], and an increase in frequency and quality of the interactions [37].

School-based teleconsultation has been successful in disruptive behavior consultation through videoconferencing. Further, teleconsultation was rated by the teachers as been just as an acceptable delivery medium as traditional face-to-face consultation [26, 35]. While teleconsultation has been an effective medium for instructors, studies have used them in static platforms (e.g., Kubi [8]) that do not mimic real-world interaction, in which students and teachers move frequently in their environment [34]. This is a significant limitation, because the quality of teleconsultation can be hindered if the consultant is unable to follow along and view the student's work. Thus, telepresence robots (e.g., [5, 10]) may be the best solution to the static nature of typical teleconsultation. In our work, we will be using a desktop-based teleconsulting robot to evaluate the quality of teaching in the context of an augmented makerspace.

2.3 AR for Robotics

AR technology, which is capable of creating immersive virtual interfaces, has been used for remote control and teleconsulting in human-robot interaction (HRI) research [39, 55]. Past research has explored AR interfaces in order to control the status and to plan robot activity [17, 29, 33, 40, 64]. These methods enable easy and intuitive manipulation of the robots [70], and facilitate debugging, operation, and mobility. Other AR interfaces in robotics have been used for object modeling and printing [60], education applications [27, 30], and adjustable wearable robots [68].

Additionally, spatial tasks and immersive visualizations enabled by AR are leveraged for telepresence in HRI applications [55]. For instance, AR can enable collaboration between distant users by providing them with the same virtual environment. Along these lines, users can visualize AR content superimposed with instructions or information of spatially-distributed tasks [69]. In this paper, we focus on AR information being delivered from the teleconsulting robot by the instructor. We investigate using a remote-controlled robot to provide the instructor's presence on the workspace combined with AR instructions for real-time help. The instructor is provided with a 2D interface to control the robot and create AR content (e.g., notes, drawings, diagrams). The student observes the instructions from the robot's head (i.e., the smartphone), which are superimposed onto the physical workspace.

2.4 Challenges of new technology in virtual makerspaces

In the past months, instructors were faced with a quick transitioning to online teaching. Currently, some of the most common platforms for virtual classrooms are Webex [14], Google Classroom [6], Skype [13], and Zoom [16], which is probably the most popular platform. This experimental transition has proven to be challenging, specially because this synchronous classes often lead to multi-tasking and distraction, and leave students feeling frustrated, fatigued, and complaining about "Zoom hangovers", "Zoom bombing", and "Zoom zombies" [54, 59].

In this new paradigm, the success of distance learning depends on the degree to which students find the agents of instruction (e.g., videoconferencing, teleconsultation) credible, are capable of learning from them, and find that their problems can be diagnosed with ease [32]. Credibility refers to the degree to which the students consider an instructor to be competent and an effective communicator [32]. Instructor credibility is important because it has great

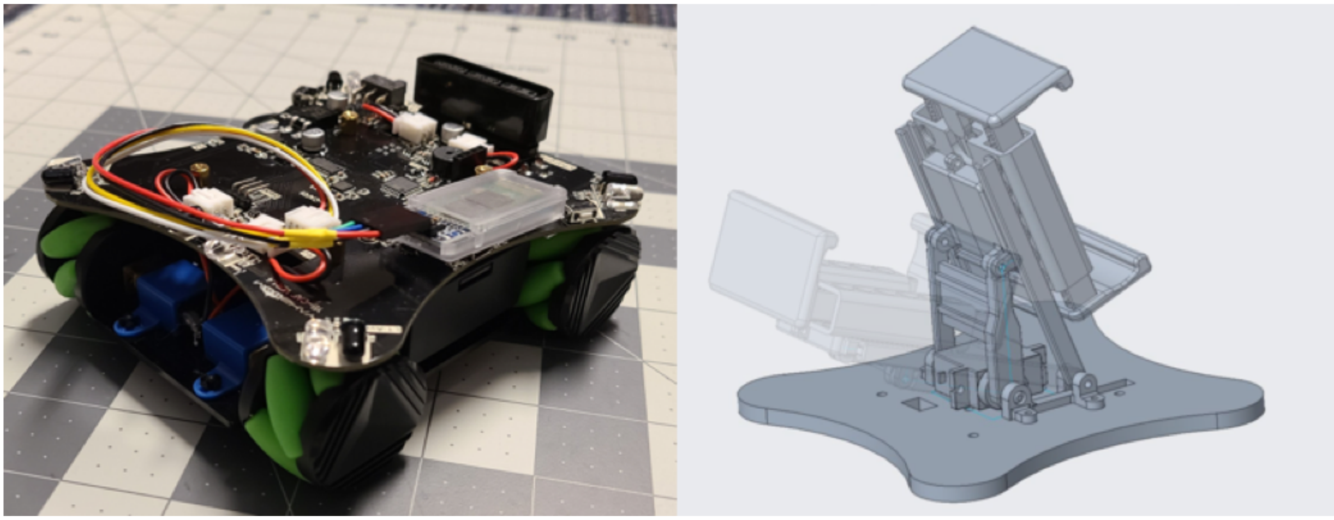

Figure 2: *Left*: Base of the robot. *Right*: Customized phone holder.

impact on the effectiveness of learning [36, 57]. In the past, credibility has focused on in-person studies of classrooms and while there is some evidence on the credibility of telepresence robots for education [32], questions arise on the effect of credibility when using teleconsulting robots, and virtual platforms and makerspaces.

Within the context of the work done in online makerspaces, we can discuss the current challenges faced by instructors. For example, when working with an Arduino board and electrical circuitry components, instructors had issues providing explanations given difficult camera angles and problematic camera zooming in on the small components [53]. While these issues can be bypassed by the instructor using multiple cameras at the station, on the students' end this remains a problem, specially when they require the instructor's help with diagnosing flaws with their circuits. Our teleconsulting robot, which has a top with two degrees of freedom, can tilt and zoom, thus overcoming the aforementioned problems encountered in virtual makerspaces. Also, our AR instructions will provide spatially distributed information, which will aid instructors in explaining clearly what the steps and connections look like when positioned in the physical world.

3 REQUIREMENTS ELICITATION

Since STEM distance learning in virtual makerspaces presents its unique set of challenges, we wanted to understand how an AR-compatible robotics toolkit would be an appropriate solution to this context. We interviewed 4 instructors and 10 students who had participated in previous full-day sessions of an online makerspace over an 3-day period, in which the participants took part in engineering activities and learned basic electrical circuits. Two of the instructors had more than 2 years of experience with physical makerspaces and workshops, and two had volunteered for their first virtual makerspace. Instructors were encouraged to reflect on their experiences by responding to the semi-structured interview. We conducted separate interviews with each instructor over a 1-hour period. Interviews with students were surveys completed voluntarily.

3.1 Findings

Students expressed appreciation and contentment for their instructors and their quick adaptation to the new format of distance learning. Overall, students and instructors showed a positive attitude towards virtual makerspaces; however, this enthusiasm was mostly related to the opportunity of realizing the activity at all, instead of getting cancelled, and of using technology in a meaningful way. Also, they recognized several issues with these new interactions and the way in which problems were solved among participants.

(R1) Need for teleconsultation for proximal demonstration. Students reported missing aspects of physical makerspaces. More specifically, they felt a lack of demos "on-the-fly". Face-to-face sessions meant that the instructor walks toward their workspace and sometimes, quickly shows a student a short example of something they did not understand or instructions from which they fell behind. This provided encouragement and support to continue working on the material. Similarly, instructors reported that the ability to diagnose a problem depended on them being able to approach students and analyze what was wrong with their work.

(R2) Need to reshape the landscape. An instructor pointed out that screens can be limiting and lack 3D perception of what the instructions look like. There was a consensus among instructors that they see the future of distance makerspaces to provide learners with a more immersive interface, such as mixed or virtual reality.

(R3) Need for reshaping the hardware. Instructors and students all reported issues with videoconferencing when instructors wanted to hold components or demos towards the camera, and when students needed to show their progress and request help with problem-solving. Our technology needs to solve the aforementioned issues in terms of facilitating zooming, centering, and

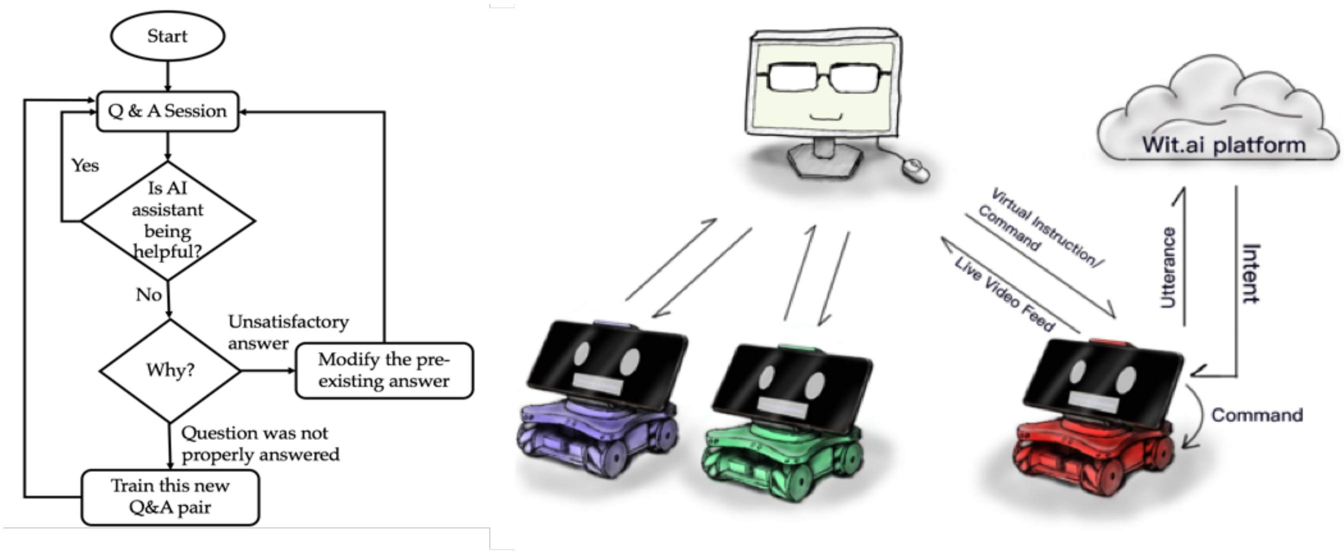

Figure 3: *Left*: Flow chart for iterative training process. *Right*: Network architecture.

adjusting the camera angles. More importantly, the hardware has to tilt, zoom, and move so that instructors and students can capture any area of interest within the workspace.

(R4) Need to relieve the instructor. Virtual learning can be difficult, specially when trying to diagnose problems and communicate instructions from a screen. Instructors reported that about half the time of the session was allotted for debugging and troubleshooting of students' errors. In order to alleviate the burden placed on instructors, we should have an initial helper in the form a AI voice assistant, which can provide hints to help solve issues with the work; thus, teleconsulting instructors takes place if students are not satisfied with the aid or if they would like check-ins.

(R5) Need for a scalable architecture. we need to support cloud capabilities to enable multiple students to simultaneously participate in an augmented makerspace. Students reported that much of the vibrancy of makerspaces is due to the community of makers to showcase and demo their work between makers of different skill levels.

4 SYSTEM OVERVIEW

4.1 Hardware Platform

4.1.1 Base. The robot's base (11.5cm x 11.5cm x5cm) with its main components is shown in Figure 2 (Left). The onboard microprocessor ATmega328P controls the behavior of the robot by taking command signals from the Bluetooth module HC-06 and translate them into actuation signals driving the electric motors. The Mecanum wheels on the bottom are designed to move in any direction without turning the direction of the wheels. It is perfectly suited for constrained spaces such as students' desktops. The 6000mAh battery powers the robot to work for about 1.5 hours without recharging.

4.1.2 Customized Phone Holder. We designed and 3D printed an adjustable holder, as seen in Figure 2 (Right), to mount the phone on top. The remote-controlled servo motor attached can alter the holder's tilt angle from 25 to 70 degrees. It gives instructors the flexibility to change the viewing angle and to focus on areas of interest in real-time.

4.1.3 Smartphone. The smartphone is responsible for multiple tasks. It captures student's workspace with its rear camera and streams it to the instructor's side. Corresponding instructions are then subsequently forwarded to the phone. The commands to the robot are also routed through the phone before they reach the microprocessor. There is no special requirement for phones, as long as they are AR-compatible. A student can use his or her own phone to work by simply mounting it on the holder and pairing it with the Bluetooth module.

4.2 Software Implementation

4.2.1 AI Voice Assistant. Our elicitation requirements found that there is a need to relieve instructors from answering similar questions repeatedly throughout the session. To tackle this problem, we trained an AI voice assistant responsible for providing hints or direct answer–to a common set of questions we trained for the makerspace session–using the Wit.ai framework[15] which has advanced natural language processing capability. If the AI assistant understands the questions asked, it instantly displays pre-logged answers on the screen. To create a competent AI assistant, which can recognize questions comprehensively and provide the most accurate answer, a sufficient number of questions and answers are needed for training. We designed an iterative scheme to progressively train the assistant as seen in the schematic of Figure 3 (Left). Whenever a student finishes a Q&A session, he or she is prompted with a question asking if the AI assistant provided the appropriate answer. If not, the system automatically logs the question that was asked, for later reference by the instructor. An unsuccessful Q&A experience could be caused by two possible reasons: either the question is not properly recognized, or the answer is not satisfactory. In the first case, the instructor adds the new question-answer

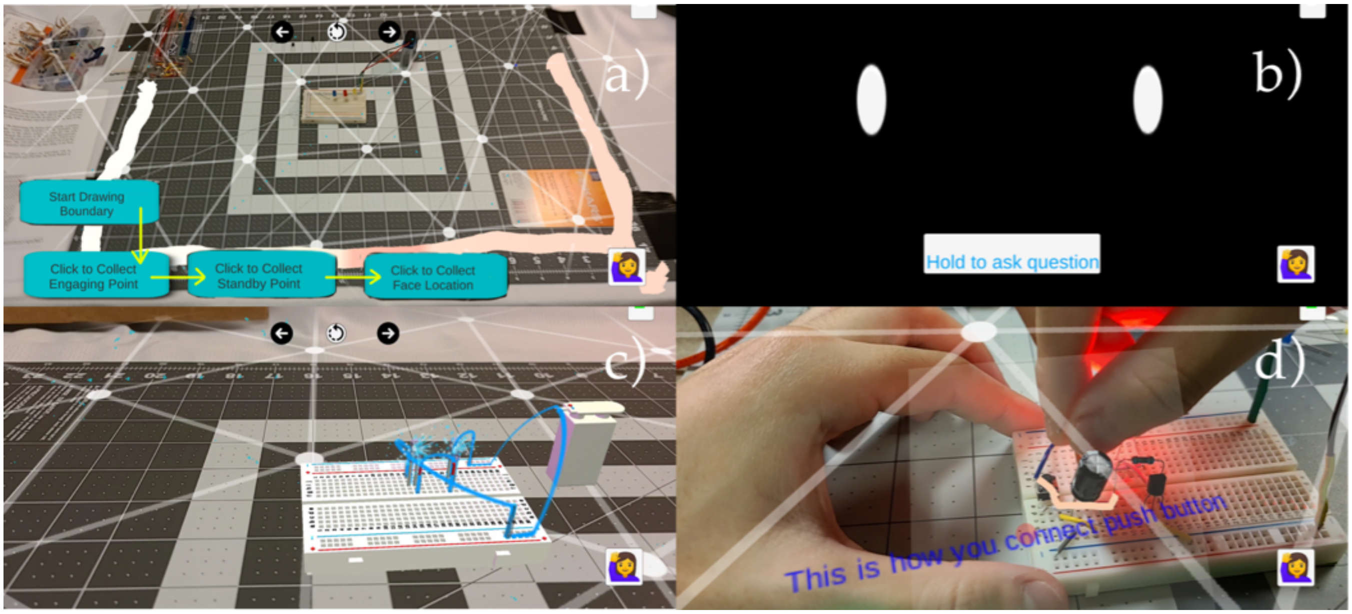

Figure 4: UI scenes on student's end. (a) *Setup*; (b) *Standby*; (c) *AR Animation*; (d) *Teleconsult*

pair into the training queue. In the latter case, the instructor can choose to modify the preexisting answer should he or she deem it necessary. If this process happens periodically, the accuracy of the robot improves over time.

4.2.2 Network Architecture. RobotAR was developed in Unity 3D, which is a game engine. The network architecture we built to interconnect each unit of the system is shown in Figure 3 (Right). First, the phone transmits the live-video feed to the instructor's computer, and allows it to receive virtual instructions and robot commands. This bilateral connection is established with the TCP/IP protocol, which ensures transmission reliability. Eventually, command signals are routed to the robot using Bluetooth protocol. Bluetooth protocol is perfect for low-cost, low-power, and short-range transmission between electronic devices. Further, since the Wit.ai is a cloud-based framework, every student's utterance to the question is posted to a remote server for processing. Subsequently, the result which represents the corresponding intent, is sent back to the phone. Both utterances and intents are transmitted using the HTTP protocol.

4.2.3 Student's User Interface. The user interface for the robot consists of four scenes: *Setup*, *Standby*, *AR Animation*, and *Teleconsult* (see Figure 4).

Setup: Students first scan the table surface using their phones. This process is used to obtain the position of phone relative to the surface. It is a prerequisite for making the virtual content appear in real-world locations. Then, students draw a safety boundary, as an enclosed circle on the phone's screen, that represents the robot's available area for movement (i.e., workspace). Finally, students are required to designate "Standby Point", "Engaging Point", and "Face Location", respectively. Standby Point is the position in which the robot stays idle. Engaging Point is the initial position the robot moves to, as soon as teleconsult mode begins. Face Location is the position of the student's face. This information allows us to ensure the phone's screen always face the student, regardless of where the robot moves to. Drawing boundaries, determining facial position with respect to the 3D space, and defining spatial points are supported by the computer vision algorithms provided by ARCore development kit [1], in which the camera extracts feature points of the area to transfer 3D coordinates information to the system.

Standby: When the student is not in need of help, the robot moves itself aside while remaining in the field of view. If a problem occurs, the student can ask the AI voice assistant directly or enter the Teleconsult mode. In the first case, answers in texts and images are displayed in the current scene. In the second, it moves to Engaging Point.

AR Animation: We added several AR animations to introduce abstract concepts to students. These animations–which are initially displayed at the beginning of the session–can always be reviewed by students when scrolling back to this scene. Compared with traditional text-based or video-based tutorials, AR delivers a richer user experience and conveys spatial information which is important to hands-on tasks.

Teleconsult: Once the robot enters Teleconsult mode, it moves to the Engaging Point to assist the student. During this period, the robot behaves as an agent for the instructor. Thus, the robot can travel both manually and automatically. RobotAR starts from an initial position for teleconsulting. Its location is typically set at a point in which the camera can have a full view of the workspace. Then, the robot will automatically travel to this point and remain in place, until the instructor chooses to manually move the robot. Detailed information on how instructions are carried out will be discussed in the latter section.

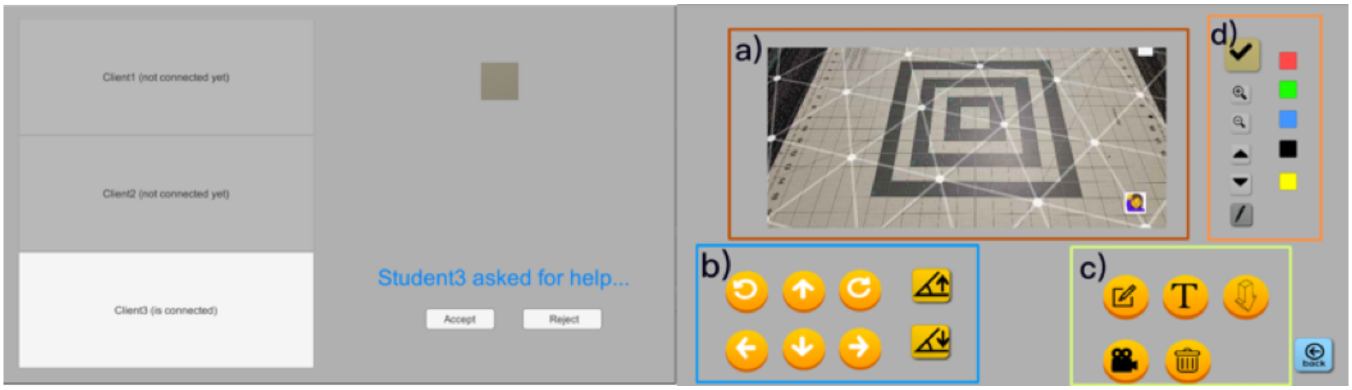

Figure 5: UI scenes on instructor's end. ***Left: Connection. Right: Instruction.***

4.2.4 Instructor's User Interface. The user interface for the instructor is designed for the computer platform. It consists of two scenes: *Connection* and *Instruction* (see Figure 5).

Connection: Each student's teleconsulting request is shown in this scene. Once it is accepted by the instructor, a one-on-one connection with the student is established. If a request is initiated when the instructor is unavailable, the student is notified and placed in queue.

Instruction: This scene can be separated into four regions. The live view window (see Figure 5a:Right) shows the student's real-time workspace. The command panel (see Figure 5b:Right) enables the instructor to operate the robot by moving it in any direction and tilting the angle of the phone holder. The content creation panel (see Figure 5c:Right) provides a variety of options for instructors to deliver real-time AR instructions. They can draw spatial lines, write text descriptions, add indicating arrows, and send out live-demos. Except for the live-demo which takes up the entire screen, other instructions will be superimposed on the student's screen as AR content. Instructors can further change the size, color, and positions of the instructions via the customization panel (see Figure 5d:Right). By default, students and the instructor are able to talk to each other throughout the process.

5 EVALUATION

We performed a user study to test our setup and its effects on an augmented makerspace, involving a hands-on session between instructors and makers (Figure 6). In this user study, we mimic the methodology being used by instructors in virtual makerspaces and compare it to our robotics toolkit. Thus, we split our experiment into two conditions: (a) Videoconferencing with Zoom, (b) RobotAR, which includes AR delivered instructions, the voice assistant, and the option of teleconsulting. We decided to juxtapose our toolkit capabilities with the technology currently used and available in virtual makerspaces. Then, we will analyze how the effect of our toolkit for the instructors, the students, and the interactions between them.

5.1 Setup

First, the context of the class was a three-part single session–using RobotAR or Zoom, in which each participant was in a separate room. Each part lasted about an hour and there was a short break (5-10 mins) in between each hour. Likewise, the instructor was in another room, but given complete vision of the student's workspace via Zoom or our platform. There was at least one researcher physically present with each participant, while the participant teleconferenced with the instructor as necessary. Due to conflicting schedules and availability of robots, we had the instructor teach each session to 3 students at a time for both conditions. For the RobotAR condition, each student was provided with a robot; while for the Zoom condition, each student was provided with a tablet.

We chose a crash-course introductory lesson on basic electrical circuitry, which is part of an undergraduate class on electrical circuitry and programming. The series included the following parts: *Using basic tools*, *Connections in series and parallel*, *Transistors and capacitors*. We selected this use case due to the following reasons: (a) we had access to a robotics instructor, undergraduate curriculum for the class, and the students' kits from previous classes; (b) circuitry and tools are the most used subjects in makerspaces.

Thus, each session was split as follows: (1) Lecture part, in which students got introduced to the material, received some demos, and discussed the new concepts; (2) Hands-on making, in which students attempted to complete all activities on their own, and requested instructor's aid if necessary. The lecture part lasted about 30 minutes and the rest of the session lasted about two and a half hours. In the Zoom condition, following the lecture part which included some live-demos, students were able to teleconsult the instructor any time they required help. In the RobotAR condition, during the lecture part, students received the demos via AR. During the hands-on making, they were able to use the voice assistant first, then teleconsult with the instructor via the robot if they wanted help, clarification or a check-in.

5.2 Instruments and Activities

We gave each student with a Makeronics (7 in 1) electrical circuitry components kit, so they could participate in the experiment. These are the components from the kit which were used for the session: a breadboard, jumper wires, capacitors, LEDs, buttons, transistors, resistors. We also provided a multimeter for each student to take measurements of current and voltage, and verify connections. Since our audience had little knowledge in circuits, the activities at each of the

Figure 6: *Left*: Student A works on her circuits. *Middle*: Student B teleconsults with instructor. *Right*: Student C uses the voice assistance.

three parts involved a short lecture on basic tools and components (e.g., LEDs, wires, batteries, multimeter) with instructor-guided circuits (e.g., 2 LEDs in series and 2 in parallel), and a self-guided follow-up circuit (e.g., combined series and parallel circuits, while writing down measurements of voltage and current).

5.3 Participants

We recruited 24 participants (15 male, 9 female) ranging from 20 to 28 years old (M=22.3, SD=2.65), all of which had experience with online classes and virtual laboratories, but little experience with electrical circuitry or virtual makerspaces. Participants were distributed in groups of 3 students per each session. The instructor leading all the sessions for both conditions had more than 2 years of experience teaching robotics classes and giving workshops at physical makerspaces. 15 of our participants had previous experience with voice assistants, 2 had prior experience with robotics, and 10 had experience with AR applications.

6 RESULTS

6.1 Pre- and post-test evaluations

Since we are aware that electrical circuitry performance goes beyond whether the circuit is working or not, we decided to establish a coding scheme to evaluate conceptual knowledge and hands-on performance. Past work has shown that important circuitry concepts are pervasively misunderstood well into adulthood [56]; thus, we decided to test participants on these concepts in the pre- and post-assessment (after the 3-hour session) tests. Additionally, we tested on whether students were able to identify the appropriate schematic diagrams of the circuits they were building. For example, the participant may use redundant connections to complete a circuit. Similarly, students may be able to calculate and measure voltage and current, but may not understand them conceptually. Each answer was scored with a 0 if incorrect, +0.5 if answer had some substance, or a +1 point if correct. Then, the total points were normalized to fit into the 1-point scale for each category. Past work on circuitry has proposed similar coding schemes and categories to score circuitry learning [61, 62]. The categories we considered for evaluation were the following:

Knowledge of voltage and current conceptual and applied understanding of voltage and current; *Polarized component orientation:* the positive terminal (+) of polarized components are consistently oriented toward the positive terminal or pin(s) of other components; *Connections in series and parallel:* successfully connect one component to another in series or parallel, as well as knowing its effects on voltage and current; *Knowledge of circuitry components:* functionality , placing, and connecting LEDs, resistors, push buttons, capacitors, transistors, batteries; The next key competencies did not have a pre-test because they included calculations from hands-on performance. *Use of breadboard:* appropriate placing of components to power and ground rails and in respective rows; *Use of multimeter and measurements:* measuring resistance, voltage, current, conducting short tests; *Working circuit:* using appropriate components, wires, and making sure the circuit is closed.

4 Key competencies were analyzed by coding pre- and post-tests, graded on a 1-point scale. While 3 other key competencies were obtained by collecting the answers from lab manual (test). All tests were coded by one primary coder. Inter-rater reliability on both the pre-test, test, and post-test was validated by having a secondary person score over 25% of the data. From our rubric, two researchers in charge of grading had a Cohen's Kappa of 0.714. As for the workshop, we had to wrap it up at the 3-hour mark. From the Zoom condition, only 3 out of the 12 students managed to complete all the exercises available. While, 7 out of the 12 students managed to complete them from the RobotAR condition. The rest of the students oscillated between 25% to 75% completion of the exercises. As for the results of the pre-test, test, and post-tests by condition, these are summarized in Table 1.

We analyzed scores with our aforementioned rubric for the key competences assessment. We began with a Shapiro-Wilk normality test to verify whether the normal distribution assumption was not met. Thus, to analyze the significance of our results from RobotAR and Zoom conditions, we conducted the Friedman Test with a post hoc analysis from Wilcoxon signed-rank test. When comparing these conditions, the Wilcoxon sign-rank test showed a statistically significant improvement for RobotAR condition in 3 out of 4 conditions: *knowledge of voltage and current* [Z=-2.333, $p<0.05$, p=0.02]; *connections in series and parallel* [Z=-2.084, $p<0.05$, p=0.037]; *knowledge of circuitry components* [Z=-2.12, $p<0.05$, p=0.034]. Likewise, the learning gains between pre-, post-tests are presented in Table 1.

For the remaining key competencies, which are the scores obtained from the lab manual students returned, we also performed

		Zoom		RobotAR		
Key Competency	**Time**	**M**	**SD**	**M**	**SD**	**Sig.**
Knowledge of voltage and current	Pre-test	0.246	0.263	0.254	0.235	*Z = -2.333* *p < 0.05*
	Post-test	0.842	0.07	0.813	0.092	
	Gain	**0.790**		**0.749**		
Polarized components orientation	Pre-test	0.153	0.246	0.169	0.262	*Z = -1.095* *p > 0.05*
	Post-test	0.813	0.084	0.788	0.068	
	Gain	**0.779**		**0.745**		
Connections in series and parallel	Pre-test	0.138	0.123	0.163	0.136	*Z = -2.084* *p < 0.05*
	Post-test	0.596	0.214	0.763	0.146	
	Gain	**0.531**		**0.717**		
Knowledge of circuitry and components	Pre-test	0.167	0.155	0.191	0.166	*Z = -2.12* *p < 0.05*
	Post-test	0.525	0.221	0.767	0.259	
	Gain	**0.430**		**0.712**		
Use of Breadboard	Test	**0.646**	0.155	**0.804**	0.144	*Z = -2.771* *p < 0.05*
Use of multimeter and measurements	Test	**0.508**	0.155	**0.717**	0.228	*Z = -2.998* *p < 0.05*
Working circuit	Test	**0.479**	0.13	**0.697**	0.21	*Z = -2.053* *p < 0.05*

Table 1: Pre-test, test, and post-test results of key competencies assessment.

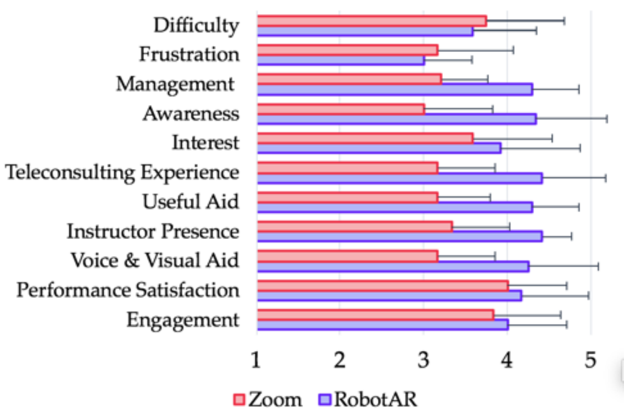

Figure 7: Results from average scores on the usability of RobotAR vs. Zoom. Purple: RobotAR, Red: Zoom videoconferencing. We used 5-point Likert scale (1-strongly disagree, 5-strongly agree). (*) : p<0.05).

the Wilcoxon signed-rank test and found for that RobotAR condition showed a statistically significant improvement in all 3 competencies: *use of breadboard* [Z=-2.771, p<0.05, p=0.006]; *use of multimeter and measurements* [Z=-2.998, p<0.05, p=0.003]; *working circuit* [Z=-2.053, p<0.05, p=0.04].

6.2 Usability Evaluation

After the 3-hour user study session, we provided participants with a 5-point Likert scale (1-strongly disagree, 5-strongly agree) questionnaire. This survey was meant to assess the usability of RobotAR vs. the traditional teleconferencing media, Zoom. Figure 7 shows the average scores reported by participants. These results were representative of the following categories: *Engagement*; *Performance satisfaction*; *Voice and visual aid* from the system; *Instructor presence*; *Useful aid* from the instructor in real-time; *Teleconsulting experience*; *Interest* in the subject; *Awareness* of instructor; *Management* by instructor; *Frustration* with problem-solving; *Difficulty* of the learning material.

We conducted a Mann-Whitney U test on each of the categories. Thus, from the reported responses, we found participants preferred usability of RobotAR condition for the following (p<0.05): RobotAR (M=4.25, SD=0.829) provided a higher quality of voice and visual aid with its system than Zoom videoconferencing (M=3.167, SD=0.687), U=110, p=0.007; RobotAR (M=4.417, SD=0.344) improved the overall instructor presence as compared to Zoom videoconferencing (M=3.333, SD=0.687), U=131, p=0.000; RobotAR (M=4.292, SD=0.557) allowed the instructor to provide more useful aid in real-time than Zoom videoconferencing (M=3.167, SD=0.624), U=128, p=0.001; RobotAR (M=4.417, SD=0.759) provided a higher quality of teleconsulting experience than Zoom videoconferencing (M=3.167, SD=0.687), U=135, p=0.000; RobotAR (M=4.333, SD=0.849) provided greater awareness of instructor than Zoom videoconferencing (M=3, SD=0.816), U=126, p=0.001; RobotAR (M=4.292, SD=0.557) instructor's management of student's workspace than Zoom videoconferencing (M=3.208, SD=0.557), U=130, p=0.000. For the remaining categories no statistically significant differences were found (p>0.05): Engagement (RobotAR: M=4, SD=0.707; Zoom: M=3.833, SD=0.799, U=0.78, p=0.727); Performance satisfaction (RobotAR: M=4.177, SD=0.799; Zoom: M=4, SD=0.707, U=81, p=0.6); Interest (RobotAR: M=3.917, SD=0.954; Zoom: M=3.583, SD=0.954, U=83, p=0.505); Frustration (RobotAR: M=3, SD=0.577; Zoom: M=3.177, SD=0.897, U=66, p=0.727); Difficulty (RobotAR: M=3.583, SD=0.759; Zoom: M=3.75, SD=0.924, U=61, p=0.506).

7 DISCUSSION

In this section, we discuss the findings of our user study and reflect on how they influence the questions we posed in the introduction.

Q1: To what extent does the use of RobotAR lead to an improvement in students' key competencies and user experiences compared to traditional teleconferencing platforms?

Students were overwhelmingly positive about RobotAR. There was a consensus among students that our robotics toolkit was a viable alternative to provide high-quality teleconsulting in an immersive, focused approach.

"It's fun, it's convenient, it's educative. I feel like I'm in a new age of learning."-P8

Our results showed that RobotAR was conducive to an improvement in assessment of key competences when compared to Zoom teleconferencing for 6 out of 7 categories: *knowledge in voltage and current, connections in series and parallel, knowledge of circuitry and components, use of breadboard, use of multimeter and measurements, working circuit.* Much of the learning that takes place at makerspaces is hands-on and through an exploration process. One common mistake among participants included which points in a working circuit were appropriate for measuring voltage or current. For example, if participants could not map the schematic of the circuit, it typically translated into a lack of knowledge on what it meant to measure voltage across the power source or across an LED. In our case, RobotAR provided students with important tools that accelerated or guided them through the discovery of these questions.

AR content. The AR animations that had been set up on the robot for the session were used in ways we were not expecting. Those animations were meant to be used as the lecture section to provide follow-along, basic information of circuitry; however, we found out that students were using those animations throughout the workshop to internalize or refresh some of the concepts they had not understood.

"In real life you can't re-play the TA."-P10, who reportedly used the AR to differentiate between capacitors and transistors and how to connect them.

There is a discussion to be had as to how much of the learning gains depend on AR, and why it should be used instead of a different technology (e.g., a video which loads on a website). In our setup, the use of AR was presented in two formats: (1) to provide tutorials for the lecture with demos for students; (2) to provide students with real-time notes/drawings from the instructor. (2) was a feature of our toolkit, enabled by the instructors' UI. This was especially useful, since access to the phone's camera and the toolkit, established the 3D coordinate system of the workspace. With (2), AR superimposes content and provides spatial information corresponding to students' specific workspace and requires no extra steps from instructors. Conversely, (1) is an optional process, since we decided to deliver the laboratory with entirely AR-based content. AR content is supported by the toolkit, but needs to be created in Unity 3D, which makerspace instructors can choose to do. However, students emphasized on the usefulness of being able to replay the content, rather than the format (i.e., AR, video), even if they found voice and visual aid to be helpful. Thus, we would recommend makerspace instructors to focus on creating tutorial content to the best of their abilities, whether in AR or typical video.

Voice Assistant. In most cases, the voice assistant was the go-to tool for participants who had a simple, quick question. For example, *"which leg is my positive side in my LED?"*; *"how do I read a resistor?"*; *"what is voltage?"*. Referred to as a *"first-responder"* (P2), students pointed out that the voice assistant helped them not get too complacent, just get a quick fix, but continue trying to solve their circuits by themselves. Similarly, students reported that it took away the anxiety of asking the "wrong question" or overwhelming the instructor.

"At first I use [the voice AI] because I don't want to rely too much on the TA...because I want to learn, so maybe I want help but not too much."–P7

"The AI helped me to not overload the TA with embarrassing questions. Simple things, [the voice AI] helps you fix."–P1

The effectiveness of the voice assistant is an ongoing process. As the database incorporates more utterances, it will become more accurate at responding to students' questions. Although incorporating more questions and answers into the database is a simple procedure, instructors–who are already in charge of all content creation–may consider whether this is a necessary burden. First, the size of the makerspace is an important detail upon which to take decisions. For example, if a makerspace has 5 instructors and 7 students, then maybe a voice AI assistant to answer questions may not be worth the effort. However, if that same makerspace has 5 instructors and 75 students, then the quantity and quality of available aid will be crucial for a positive learning experience. It should be up to instructors' judgement to decide whether a makerspace requires of the AI voice assistant feature.

Another important feature of makerspaces is brainstorming projects and solutions. This process is synergistic in a physical makerspace, because students are in close proximity, but in a virtual makerspace this is more constrained. One possible solution is for instructors to use a platform (e.g., Slack, Discord) in which students can share, brainstorm, and comment on each others' work. If so, this should take place before or after makerspace hours instead of during, so as to not distract students while they work on their projects. However, we consider the voice assistant for RobotAR–which was used during makerspace hours–to be a proxy for these brainstorming in-person sessions. After all, the AI is crowdsourced from previous sessions with students, and while it does not replace human-to-human interaction or brainstorming, it can become a placeholder to keep students engaged and feel like they are getting community support.

Instructor Teleconsulting. As for the teleconsulting, which was the favorite feature of the robot, students found the AR visual cues provided by the instructor (i.e., arrows, drawings) to be useful and engaging.

"I liked that you can contact the instructor, which is super convenient, because they can show you [the correct answer] in your scene and it's like you never left the lab."–P5

"For me, the instructor [teleconsulting] with the AR is best...it helps to accurately locate something into my view. With [the AR] there is no gap, I don't have to map from his view to my end."–P9

To provide context, the AR demos and the voice assistant were the first-stop tools of most participants. However, there was consensus among students that the teleconsulting feature–either by having the instructor make AR annotations in the students' scenes or by sharing his own camera to do a focused live-demo–was important to understand some difficult concepts that would otherwise make them fall behind. RobotAR, as an intermediary agent for teleconsulting, deviates from current makerspace practices (e.g., Zoom sessions), which require students to double as camera-men (e.g., zooming in, focusing) and creators (i.e., working on their circuits). These dual responsibilities–even with only basic phone functions–were too overwhelming and cumbersome for students. Without the robot, students had to change the position and focus of the camera, which kept their hands busy and unable to follow instructions from the teacher in order to receive timely help. Thus, while they worked on solving their problem, the tablets/phones ended up getting dropped and laying down on the table in disuse.

In terms of the documentation that instructors would typically require from their makerspaces, the lack of physicality would severely hinder instructors' ability to keep track of students' progress. In a physical makerspace, instructors walk around the classroom, glance over students' shoulders, and check progress status. However, in a virtual makerspace, these routine check-ups are difficult without interfering with students' concentration, by asking them to stop and cooperate with focusing/zooming into their workspace. RobotAR removes the need for extra work because the camera repositions according to the students' view or follows along. This is a promising step towards a pathway to have more natural interactions with distance technology, which should be the goal of all makerspaces. Also, this greatly reduces the workload of the students.

Q2: To what extent does the use of RobotAR allow the instructor to offer more on-point instruction and at a higher level during problem-solving?

"It's not just the movement of the robot, it's the voice!"–P4, who emphasized that while he liked how the robot could focus on his workspace, it was the instructor's voice–which could be heard as the robot moved along–which made him feel like the instructor was there next to him.

Several students pointed out that the combination of AR annotation plus voice from the instructor made the class content *"more interesting"* (P10).

The robot mobility and focus capabilities facilitated a higher quality of teleconsulting. Instructor had better access to students' problems, could provide visual cues and notes, and no longer had *"to worry about guiding the student to a particular area, I can use [RobotAR] to focus on what I know I'm looking for."* (Instructor). In this case, the instructor is referring to providing trouble-shooting help. The instructor reported that, for the RobotAR session, questions were not necessarily about problem-solving, but rather to ask for a check-up, more along the lines of: *"Am I doing things correctly?"*–P12. The instructor, who had previously referred to the Zoom session as *"chaotic-fun"*, expressed satisfaction at finding that students were somewhat better prepared in RobotAR condition. While this perceived increase in understanding was probably due to the other tools available (i.e., AR demos, voice AI), the instructor reported that *"it's always easier to help when [the students] get what they're doing"*. With all this in mind, the instructor was enthusiastic about the prospect of using RobotAR in future workshops.

Q3: To what the extent does the use of RobotAR increase instructor's management and presence in the workspace and promote students' engagement and interest?

As reported in the results, there was no statistically significant difference in engagement and interest between conditions. However, mean scores for RobotAR and Zoom were already fairly high to begin with. While we cannot claim that RobotAR provided an improvement in interest or engagement as opposed to Zoom, it did provide a significant improvement in user experience for several categories: *voice and visual aid from the system, instructor presence, useful aid from instructor, quality of teleconsulting, awareness of instructor, management of workspace.*

As we previously mentioned, the robot added to the teleconsulting experience, helped boost awareness and credibility of instructor and made students feel as if the instructor was next to them. P3 remarked that as *"the instructor was controlling the robot, I felt [the instructor] was here, more like his hands were in my [workspace]."*

It follows that if higher level problem-solving takes place over teleconsulting, then the instructor becomes more credible and the students are more satisfied with the level of workspace management and aid. For example, at different points throughout the experiment, students wanted to get assistance, but the instructor was sometimes busy helping out another student. If at this point, students–seeking assistance–had exhausted the resources (i.e., AR, voice AI), then they either continued problem-solving on their own or became distracted. Since our voice AI was still limited, then the available support was limited. We logged all students' utterances that were mistakenly classified or not recognized. In the future, our voice AI should continue to recognize a larger set of questions from students. Thus, while we had an engaged set of participants, we need to make sure to always have available resources to keep them concentrated in the work and not lose focus.

8 LIMITATIONS

While our network supports multiple users being part of the session at the same time; thus, problem-solving through teleconsulting is done in a one-on-one basis. This is due to the need for plane mapping so that the AR can be superimposed on the scene. For more efficient problem-solving, in the future, we will add a broadcasting option that will allow simultaneous teleconsulting for multiple people.

Also, our system only uses one of the phone's cameras during the whole process. Most current smartphones have multiple rear-cameras and switching between them will enable further view of the student's workspace to the instructor's benefit.

Currently, our robot does not have automatic object avoidance capability and relies on the instructor's navigation skill. In the future, we will add all the aforementioned functionalities to our toolkit.

9 CONCLUSION

In this paper, we presented RobotAR, a teleconsulting robotics toolkit to provide learning experience in augmented makerspaces. We introduce an AR-compatible, desktop-based robot that behaves as a tutor to the students, and as a versatile agent with access to the physical and virtual world. We performed a user study with 24 participants split into two conditions: RobotAR, a full implementation of the capabilities of our toolkit, and Zoom videoconferencing. The study involved completing a circuitry session to learn basic electrical circuitry. Our results demonstrated an improvement in several key competencies and an improvement in the teleconsulting experience provided by RobotAR condition. Also, we demonstrated that the instructor can facilitate a higher level instruction during problem-solving. Similarly, our toolkit provides an improvement in instructor's management and presence in the workspace. In this work, we advance our understanding of distance education, by removing the boundaries to high-quality hands-on learning, which is becoming increasingly important in our current society.

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