Telepresence Robotics for Hands-on Distance Instruction

Osazuwa Okundaye
awuzaso@tamu.edu
Texas A&M University

Sharon Chu
slchu@ufl.edu
University of Florida

Francis Quek
Texas A&M University

Alexander Berman
Texas A&M University

Glen Hordemann
Texas A&M University

Larry Powell
Texas A&M University

Leming Yang
Texas A&M University

ABSTRACT

Access to technology education is a challenge for broadening participation in STEM for remote rural communities that make up 20% of US public schools. Teleconferencing technology has provided some level of access to STEM teaching expertise to these underrepresented populations. Unfortunately, many challenges remain to provide quality technology instruction in remote scenarios. This paper presents, first, a pilot study that uncovered the problems faced in using videoconferencing technology for physically-predicated technical learning. Second, the paper describes a lab-based study investigating the use of telepresence robotics to better support students' hands-on technology learning. Two conditions embodying different types of instructor representations were compared: co-present instructor and instructor through a telepresence-robot. Results characterize key differences in students' experience and learning outcomes across the two conditions. We conclude by drawing implications for the designs of telepresence robotics to support hands-on STEM learning in remote scenarios.

CCS CONCEPTS

• **Human-centered computing** → **User studies**.

KEYWORDS

Distance learning, Remote instruction, STEM learning, Maker Movement, Micro-Manufacture, Public School, Apprenticeship

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1 INTRODUCTION

To participate in the future workplace, individuals must possess a firm grasp of technology and flexibility of mind to acquire new skills as work and its context continually evolves [47]. A key challenge is the shortage of instructors and instructors in STEM. This shortage is felt more acutely in rural communities where there are challenges such as having fewer opportunities for broader technology and science experiences, providing advanced coursework, and recruiting highly qualified teachers [2].

One solution to the shortage of teachers in the rural context is to employ distance and online learning [48] technology. Distance education can connect rural students with geographically distant experts [56], providing students a form of engagement by collaborating on questions or in-class problems with online instructors [5]. Virtual instruction can be as effective as face-to-face supervision and can address logistical issues stemming from the distance between university-based programs providing the STEM expertise and rural or urban schools [31]. However, this is not the case for all content areas, and students have often noted a lack of 'teacher immediacy' — a psychological closeness between teacher and students – in distance courses [10].

Current approaches to distance learning include teleconferencing for the purpose of (e.g., lecturing), in-screen sharing (e.g., for learning basic programming skills), coursework delivery (e.g., online instruction repositories) or any combinations of those mentioned. However, for some hands-on content areas, the challenge remains of providing tutoring assistance when not in physical proximity. One notable example is in the physicality that is central to Maker-based learning and its use to teach STEM effectively. Here, we refer to physicality as the coupled, active engagement of physical actions inherent to Making and Digital fabrication that serve to further materialize inherent engineering and design concepts for students [4]. Such a lens towards the coupling of physical actions in an active process is similar to how individuals might experiment with materials as noted in Donald Schön's 'conversation with materials' [51].

A major component of Making is that it may enable children to materialize and better understand design and engineering concepts [3]. This goal has been challenging to realize in distance learning where Moilanen and Vaden [37] and Chu et al. [8] cite the inherent physicality of Making as a critical impediment to online sharing of digital designs that require physical manifestation grounded in specific tools and processes.

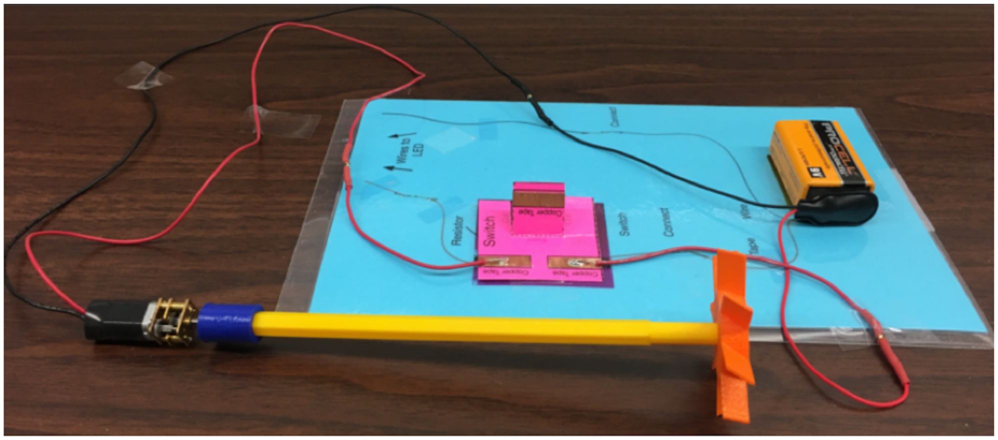

Figure 1: Kit comprising of electronics components, circuits, and 3D printed components for elementary school class on 'mixtures and solutions'.

This paper addresses how the situated and embodied communications in Making-based learning may be supported in distance learning programs. Our motivation for this research is from insights we gleaned from a longitudinal online distance learning program we offered, whereby college students acted as instructors for a daily distance learning high school Career Technical Education (CTE) course that coupled Making and production engineering coursework. Noting the challenges in instruction within the remote classroom, we sought to understand how the physicality inherent in student-teacher instruction may be realized through telepresence technology. We describe a laboratory study that simulated the experience of Making-based learning, examining how different kinds of instructor representations (co-presence - CP; mobile telepresence robot platform - MRP), may influence students' Maker learning and teacher interaction outcomes.

Our paper is organized into 4 parts. First, we describe the insights we noted in the challenges in supporting hands-on physical content in a distant online high school (CTE) course. Second, we will provide an overview of relevant work that informs the existing need for remote instruction coupled with embodied communication support. We also highlight existing work in MRPs and identify how these may support hands-on activities in distance instruction. Third, we describe a laboratory study that compares the use of an augmented MRP with in-person instruction Making-based learning scenarios. Fourth, we describe both quantitative and qualitative results from the lab study and conclude by contrasting the strengths and weaknesses across instructor representations to draw implications for the design of future MRPs for distance hands-on instruction.

2 BACKGROUND

2.1 Making-Based Learning

The 'Maker Movement' is characterized by the concurrent development in advancements in fabrication technology, the availability of core electrical and computing components, and the greater accessibility afforded in programming languages and libraries [18]. The collection of hobbyists and professionals represents the Maker movement, working together to create highly customized and functional products for use. Products developed through this movement include software libraries, fashion apparel, home decoration or everyday devices [28]. Through this movement, customized technology artifacts can now can now be created by a diverse audience at greater frequency and higher level of sophistication of design. Making has a wide range of definitions (e.g., [21, 26, 32, 55]) as well as ongoing debate as to what technologies and practices it comprises. While we recognize the diversity of views on Making, we take the position that Making involves the construction of artifacts via the joint use of technologies such as basic electronics, 3D fabrication equipment, and computer programming.

2.2 The Maker Colonias Program

The Maker Colonias program was a 3-year pilot program whereby high school students in remote areas were exposed to a combination of Making [19, 42] and rudimentary engineering skills, knowledge, and practice through distance apprenticeship with Texas A&M University [39]. The program engaged high school students in the Colonias (defined formally as unofficial settlements along the US-Mexican border that are typically severely under-resourced [66]).

The program involved a Career Technical Education (CTE) course whereby a team of high school students were taught essential Making and manufacturing skills. At the remote high school, the class was conducted in a customized Makerspace in a classroom equipped with soldering irons, hand tools, inventory for basic electrical wiring, and a 3D printer. Through the course, students are taught how to independently produce and manufacture instructional kits (Figure 1) for a nearby elementary school, acting as a small scale manufacturing plant, creating low-volume, highly specialized products. The class was conducted via online video teleconferencing by university students (graduate and undergraduate) under supervision by the research team (Figure 2). Acting as instructors, university students provided a visual demonstration of Making practices troubleshoot technical issues encountered by students, and provide verification of in-progress work.

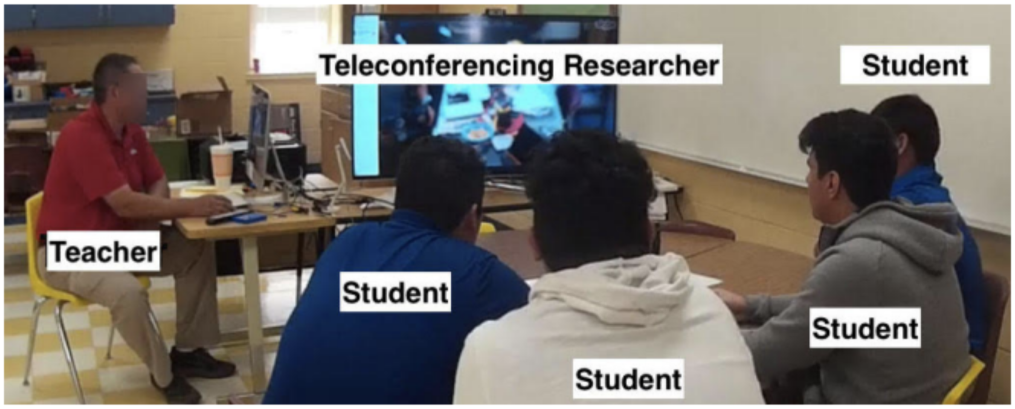

Figure 2: College students at a distant university met daily with the students at a far-rural high school at the US-Mexico border via video teleconference to provide instruction and guidance, hence engaging in a kind of distance apprenticeship

Through our experience in the Maker Colonias program, we identified issues that affected both students and teachers. Student experience was characterized by long feedback cycles for help, information, instruction, and guidance. This is a result of the communication overhead stemming from the need to manipulate the teleconference camera to view the student's projects (e.g., students move their circuit to the camera when soldering an electronics board). Teacher experience was characterized by the complexity of providing instruction for hands-on tasks. Detailed instructions were needed, along with much repetitive speech. When the instructor gave only general guidelines, students were left to explore how to do the physical task by themselves.

Moreover, during student demonstrations of their work, the instructor engaged in extensive speech to have the students spatially manipulate the object in such a way that he or she can make proper assessments (e.g.,"Turn it the other way. No not like this, I mean like that."). While the CTE Maker course was successful as an ongoing program for broadening Making experiences for rural populations, the challenges noted impeded the students' learning and experiential outcomes.

3 RELATED WORK

3.1 Need for Embodied Communication Support

Given the physicality that comes with Maker-based learning, due consideration is needed toward how design and engineering concepts are explained by instructors and understood by students. To understand how technical explanations are enacted physically, we turn to Randi Engle's research on multimodal coherence in physical explanations in which she had participants explain the functioning of a cylindrical lock to conversants [11, 12]. The explainers had access to one of three 'modes': the physical lock for demonstrations, explanation diagrams, and drawing. Engle observed, for example, how an explainer would indicate viewpoints from which an explanation is addressed. Subtle shifts in the direction of pointing, direction from which gaze is cast, and poses of the hands over the resource cue the conversant into whether the discussion is on how

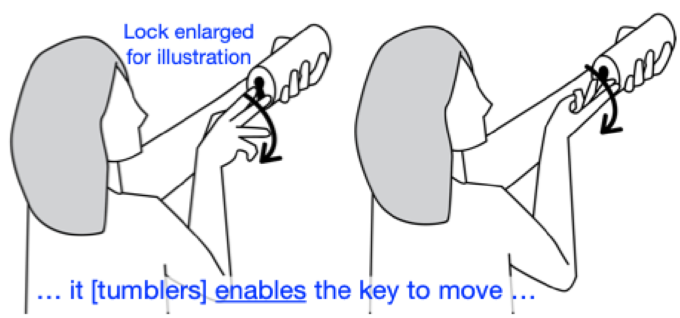

Figure 3: Direction from which gaze is case and pose of hands indicates to conversant on viewpoint inside keyhole.

the tumblers work from the viewpoint inside the keyhole (Figure 3), or the top view of the locking mechanism, or the overview of the lock as a whole. These subtle shifts are similar to the 'origo' concept [45, 46] where discourse may be segmented into larger chunks by observing shifts, not of the object being referenced, but the perspectives from which the reference is made [7, 20, 30]. Consideration to origo informs the use of MRPs in distance learning. For the distant instructor, the MRP provides a reference point, the origo, giving them a body that can interact with the distal, physical space. The distant instructor, now possessing a perceivable body, can now engage in perceivable action. Together this viewpoint communication may enable the distant instructor and students to achieve common ground and therefore to engage in more powerful expression.

Gaze and the awareness of an interlocutor's gaze are powerful mechanisms by which interlocutors coordinate their discourse and maintain context in dialog [34]. When gaze is employed while speaking, it can serve multiple purposes including deixis (pointing), regulating turn taking, pragmatic purposes (e.g., looking at a project while talking about it), and signaling attention [35]. In dialog, gaze and gesture (particularly deixis) function together to build meaning. Clark observed how gaze and gaze awareness serve to establish and build on 'common ground' in an ongoing dialogic 'project' [9].

In communicating mathematics and science/technical subjects, gesture and gaze have been shown to play a role to support thinking in the speaker and uptake of meaning for the listener. In technical and mathematical discourse, the psychological link between imagistic and mathematical/science thinking has been observed in dialogues between professional [33] (p. 166-169) and student mathematicians [60]. Smith showed that interlocutors are able to pick up on gesture and gaze to diagnose a problem in understanding and provide a solution even when a speaker is not able to fully articulate the nature of the problem [60].

For distance learning, students may be better able to understand instruction if they are given access to where the instructor is looking [52, 54] and teachers can use the students' gaze patterns to assess their attention [53]. For joint physical tasks, various studies have shown how joint gaze awareness facilitates collaborative physical manipulation [63]. Jermann, Nussli, and Li [23], for example, showed that awareness of a partner's gaze in a collaborative tetris game can improve cooperation and performance.

3.2 Mobile Telepresence Robots

MRPs refer to robotic configurations that are best described by Tsui et al. as "embodied video conferencing on wheels". MRPs have been utilized for their ability to support social presence for a remote pilot by providing a degree of physical co-presence the remote participant [29, 40, 49]. MRPs have been proposed as early as 1998, with Paulos and Canny introducing their MRP in their PRoP robot. Today's MRPs are quite similar to PRoP and have been applied in the areas of telerobotic surgery [57, 67], military operations [58], disaster recovery and surveying [6], home care [36], people with special needs [64], language tutoring [27], and telework and social collaboration [40, 49]. There has been long-standing interest in applying telepresence in distance education [15] with much of this taking the form of traditional screen-based video teleconferencing lecture/classroom instruction frameworks [23, 27].

Literature on the MRPs for distance instruction is concentrated in distance medical training, for such applications as operating room teaching and monitoring by surgeon [1, 59] and teachinf medical-surgical nursing skills [50]. A commonality that these works share is that they couple the MRP with additional cameras to provide the distant instructor a view of the classroom (i.e., addressing multiple students) as well as the individual student (i.e., addressing the student's individual work).

MRPs enable the distant instructor to have a sense of presence for students' activities. Potentially, when MRPs are coupled with additional cameras, they could enable distant instructors to possess an augmented presence, allowing for comprehensive awareness of student groups and individual activities. If we consider the origo concept, the inclusion of the camera and the additional video display, serves to establish common ground between the distant instructor and student, where the student can understand what the instructor would see from their perspective.

4 RESEARCH QUESTIONS

The insights we gained about the challenges of remote instruction using teleconferencing technology, telepresence robotics to support remote hands-on instruction. Our work addressed the following research questions:

- **RQ-I:** Are student variables (i.e., Maker Mindset, Making and Design self-efficacy) significantly different between instructor representations, co-present (CP) and mobile robot platform (MRP) across pre and post-test evaluations?
- **RQ-II:** What experiential differences are there in student-instructor interactions when the instructor is CP and represented as a MRP (e.g., when the student encounters a technical issue in an electrical circuit the instructor will either examine the circuit up close or ask the student to bring circuit to the camera.)?

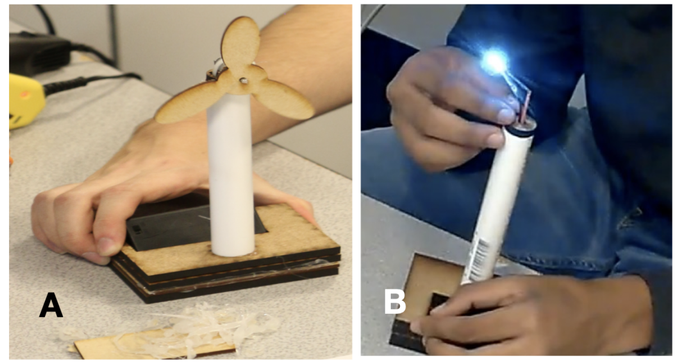

Figure 4: A) Rotational motor windmill Maker project B) LED candle Maker project

5 INSTRUCTOR EMBODIMENT LABORATORY STUDY

5.1 Study Description

We conducted a between-subjects study in the form of two Maker workshops to investigate the use of MRPs for distance instruction of hands-on physical content. The Maker workshops involved high school students constructing an 'LED candle' with an LED mounted on top of a segment of PVC pipe on top of a laser-cut base and a 'Motor Wind Mill' with a rotational motor positioned on a PVC pipe connected to a lasercut windblade (Figure 4). Through the workshop, students learned both in-screen design skills with the TinkerCAD online design software and physical fabrication skills such as wire soldering and heat-shrink application. The workshops were led by a makerspace manager acting as the teacher for the workshop. For the purposes of clarity, we will refer to the makerspace manager as instructor for our study. The study had a single independent variable, *instructor representation*, which had two levels: 1. Co-present instructor (CP); 2. Mobile telepresence robot platform (MRP). In terms of dependent variables, two were examined, these being 'Maker Mindset' and 'Maker Self-Efficacy', described further in section 5.4. For control, the laboratory manager was the instructor for both condition throughout the study. We recorded interactions beween the instructor and each group in session.

Figure 5: View of classroom setup.

5.2 Study Protocol

Both workshops lasted 4 hours and 15 minutes. The protocol of the workshop is described as follows.

5.2.1 Pre-Study. Students were given the study brief to and consent forms to review. Two pre-study surveys were administered; details of the measures in the questionnaires are noted in the upcoming subsection "Measures".

5.2.2 Study. After signing the consent form, students were given an introduction to the LED candle project. Part 1 of the workshop was characterized by short lessons on tools and direct guidance was given on their use. First, students were taught how to use TinkerCAD for approximately 10 minutes. Afterwards, students were directed to modify existing candle designs in TinkerCAD for an average up to 30 minutes. After the students completed their designs, the instructor held a 5 minute lecture on using a laser cutter. Students were then given a 10 minute lesson on soldering and asked to use soldering skills in assembly of their candles, this for up to 50 minutes.

Part 2 of the workshop resumed after the students' 5 minute break. When students resumed, they were given a 10 minute introduction to the second part of their project, this being the design and construction of a windmill. Using their acquired skills from part 1, the students used TinkerCAD to create a windmill design from an existing ".stl" file, this lasting up to 45 minutes. After the students designed their windmills for the allotted time, they were instructed to begin the physical fabrication phase of the workshop. Here, the participants took turns to use the laser cutter while one participant used the machine, the others would continue to prepare their pieces. Those who had their cut piece proceeded to assemble and solder their windmills. Physical fabrication lasted for up to 60 minutes. Figure 5 illustrates the setup of the classroom. Most students worked in pairs were given their own shared deskspace to work on the projects. For the students who worked alone, they had similar interactions with the instructors as the other paired groups. The classroom space separated from the lab where the instructor was situated by a corridor.

5.2.3 Post-Study. Upon completion of their windmills, the students were asked to complete two surveys to quantitatively assess their experience of the workshop. In addition, a single post study questionnaire were administered to account for participants thoughts and experience after the workshop; details of these measures are listed in subsection "Measures".

5.3 Study Participants

A total of 16 high school students participated in the study. Participants were recruited via an university mail service advertising to parents. There were 9 students in the CP condition and 7 for the MRP condition. There were two female students in the CP condition and the MRP condition was all male. Students' ranged in age range 14 to 18. Two students dropped out before the MRP condition of the study began.

5.4 Measures

Two pre-post study measures were administered. The first measure followed a 7-point Likert scale using the Maker Mindset Assessment [14]. The assessment consisted of 11 items that measured core facets of Making including creativity and teamwork (e.g., *"I am willing to help other people"*, *"I like to share things I make with other people"*). The second pre-questionnaire measured the student's self-efficacy on Making (e.g., *"I feel I am very good at engineering"*) and Design (e.g., *"Being good at engineering is an important part of who I am"*), using an adapted version from the 'Sources of Self Efficacy' scale [65].

5.5 Telepresence Robot

We used a Ohmni Labs robot for the study [38]. The MRP platform [38] featured a web-based interface for navigation, a display screen (10.1 inch high definition touchscreen) for the 'head' that contains a camera (4K resolution camera with 13-megapixel snapshot capability), and tilt control for the 'head display' (Figure 7). Field of vision for camera of the 'head' is 140 degrees. The 'head' of the MRP was mounted vertically, with an overall height of 4 feet and 8 inches. Speed of the MRP during traversal can vary from its lowest speed setting of 3.2 feet per second or 2.2 mph. The 'MRP' platform has a web interface platform as shown in (Figure 8). The MRP featured a close-in downward-looking camera for collision avoidance. We augmented the robot with an arm camera [22] to provide a close-in view of the student's workspace that is displayed to the instructor (Figure 6). A similar camera was available to the instructor to perform demonstrations displayed on a tablet screen mounted on the mid-section of the MRP (Figure 7). In the MRP condition, we displayed the instructor's demonstrations on the large screen in front of the students so that they do not have to turn around to see the demo when the robot is behind them. The laboratory manager driving the MRP was situated in a separate and closed room that was disconnected from the study room. Students were not privy to the actual physical location of the instructor.

Figure 6: MRP design in classroom laboratory study. A) Student under supervision by the instructor by MRP B) Instructor driving the MRP away from the students

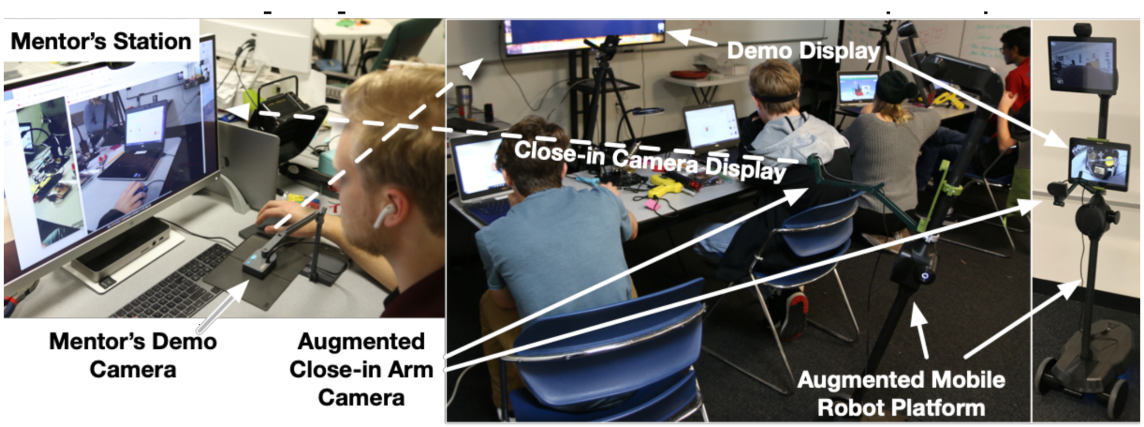

Figure 7: MRP design

6 DATA ANALYSIS AND RESULTS

6.1 Data Collection and Analysis

Video and audio data was collected for the whole workshop session. Video and audio devices were placed in front of the tables of each paired or single student. In addition, one video and one audio device were placed at the back of the classroom. A total of 16 questionnaires were collected for both pre and post tests (N= 9 for CP and N= 7 for MRP).

All the items in the Maker Mindset scale were averaged to give a single composite score for each student. That score thus represents the degree to which the student self-reports possessing characteristics of a Maker at the point of measurement. All items were averaged into composite scores as well for Making self-efficacy and design self-efficacy for each student.

We conducted a Kruskal-Wallis H test to check whether there were significant differences in Making experience between the two study groups (group who participated in the CP condition and group who participated in the MRP condition). No statistically significant difference were found on any of the pre-study measures (Maker mindset, design self-efficacy, Making self-efficacy) between the CP and MRP groups, indicating that they were comparable in nature where Maker Mindset was M = 4.43 (SD = 0.40) (i.e., students evaluated that they agree that they had a mindset towards problem solving in Making), design self-efficacy was M = 3.4 (SD = 0.14) (i.e., students evaluated it was somewhat true they were skilled in design) , and Making self-efficacy was M = 4.4(SD = 1.07) (i.e., students evaluated it was somewhat true they were skilled in Making). To compare the CP and MRP conditions, we calculated the difference between the post-study and pre-study scores for all measures (except for usability and teacher help, which had no pre-study scores). These difference scores were used for further analysis. Because of the small sample size of our study, only non-parametric statistical tests were used.

For our qualitative data analysis, recorded video data and notes were coded using 'MaxQDA' [16], a qualitative data analysis software. Qualitative coding followed a grounded theory approach as employed by Charmaz and Strauss [62]. Initial codes were generated during the open coding phase. An example of a code generated during that phase is 'Robot instructor has limited field of vision to identify student'. Next, the generated codes were organized into

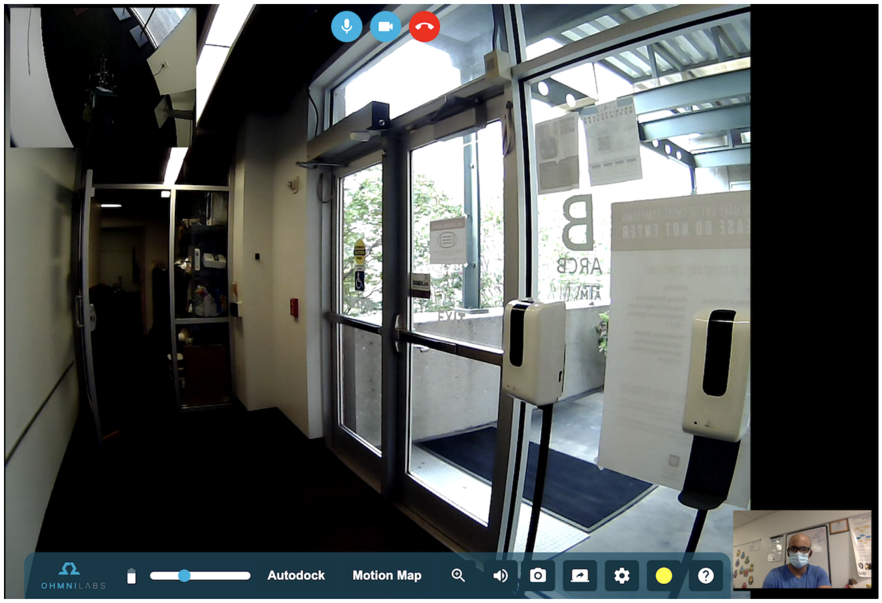

Figure 8: MRP Interface by Ohmni Labs

related categories during the "focused coding" phase. An example of a category used is 'Robot instructor had problems recognizing students' comes from the initial codes of 'Robot instructor was aware that a student had a problem but not exactly what the problem is', 'Robot instructor attempted to answer student but went to the wrong one', and 'Robot instructor cannot distinguish between students'.). Finally, thematically related categories were interrelated during the "axial coding" phase. For example, the axial code 'Robot Instructor Awareness' comes from category codes 'Robot instructor had problems recognizing students' and 'Robot instructor was unaware of students'. The coding procedure was conducted by a team of three coders. After completion of open coding by a single coder, the other 2 coders reviewed codes generated. The inter-rater agreement was at 92%.

6.2 Study Results

6.2.1 RQ I: Student Variable Differences between CP and MRP instructor. We were interested in identifying any changes in students self-efficacy or Maker Mindset from participation in the workshop. Given the small population, we ran two separate Wilcoxon signed-rank tests based on pre and post scores on Maker Mindset and self efficacy for Making and design.

Pre and post-test Maker Mindset and Making self efficacy comparison showed that no statistically significant difference between CP and MRP. Design Self Efficacy pre and post-test showed that there was a statistically significant difference for the CP group (Z = 3.5, p = 0.04) but no statistically significant difference for the MRP group (Figure 9).

6.2.2 RQ II: Experiential differences in student-instructor interactions between CP and MRP. We describe below our qualitative findings in terms of the themes that emerged from our analysis. Illustrative scenarios of the different themes are described in italics.

Student Perception of Robot: While the MRP enabled the instructor to engage students from afar, we did identify that were differences in both how the instructor perceives the distant classroom and how the class perceives the MRP instructor. We saw that the perception of the robot went through two stages of engagement with the students.

In the initial stage, the students considered the MRP a novel technology, noting the juxtaposition of the instructor's face on the screen with the MRP's body (e.g., *As the MRP entered the classroom, students fixated their views towards it, smiled, laughed as the instructor greeted the students as he directed the MRP down the classroom.*). Over time, the students acclimated to the MRP as students included the MRP as part of their conversations (e.g., *Teacher moved to P1 to see if P1 has a question. P1 remarked that he did not, stood up and moved around the robot, making light of the robot acting as an instructor*), and also in their physical, interpersonal interactions with the robot (e.g., *P1 and P4 faced a problem in their shared windmill project. When the MRP instructor was nearby, they turned their head towards the screen mounted on the robot platform and spoke to the instructor as if he was present at eye-level.*).

In this sense, the MRP was initially viewed as a proxy for the distant instructor but as interactions between students and instructors took place, the proxy was perceived as the instructor itself, possessing a body situated in physical space. Obviously, there was no such adjustment period for the co-present condition.

Instructor Awareness of Space: Much of the instructor's MRP mediated actions involved classroom traversal. MRP traversal served the purpose of managing the classroom and gaining awareness of students' activities (e.g., *P5 was not sure if he was layering the pieces using the glue gun correctly. P5 asks the instructor. The instructor moved the MRP towards P5. Afterwards, P5 showed his work to the*

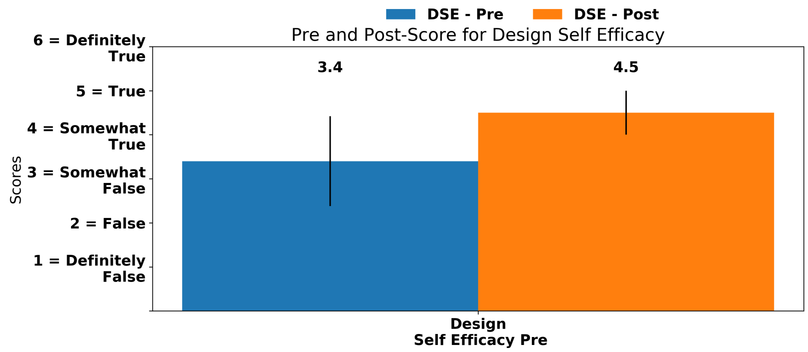

Figure 9: Comparison of pre and post Score for Design self Efficacy scores.

MRP's arm camera.). This is similar to an instructor physically walking around the classroom to gain an overall view of the status of the classroom. Where it differed though was the limited field of vision of the robot that limited visual understanding of what was being observed (e.g., *P2 asked "My screen is randomly moving". The instructor heard that a student asked a question but could not properly identify the correct student. The instructor went to a different student at first but then he moved towards P2.*) and peripheral awareness of the surrounding space (e.g., *P4 asked a question, teacher did not hear the student's question and was unaware that anything was uttered. An on-site assistant had to explicitly inform the distant instructor that P4 had a question.*).

We saw differences as well in where exactly the instructor would situate themselves during idle moments. For the CP instructor, he would remain standing in a given location of the classroom or adjust his current position if someone needed to move close by. Waiting activity differed in the MRP instructor case where the MRP was moved towards the center of the classroom so to avoid collision or presenting an obstruction when students needed to get up.

MRP Control and Traversal: Instructor-student interactions by the MRP followed a similar protocol as would be expected had the instructor been physically present.

First, just as a teacher would walk across a classroom to observe student activity or seek out students in need of help, this function was seen as the instructor would use the MRP to traverse the classroom (e.g., *The instructor while turning around the class understood that P2 made a mistake with a black circle icon on-screen. The instructor begins to advise the class as a whole based on monitoring students activity on their displays.*). This traversal serves two purposes, first is to communicate availability, and second is to seek out opportunities to help. The MRP supported the instructor to notice student's problems from afar and intervene immediately (e.g., *P4 asked "How should I make my shape longer?". The instructor moved the MRP towards P4 and answered the question immediately.*). If the student's problem is not clear from the teacher's view, they could ask the student in view what the issue is and troubleshoot from there (e.g., *P1 moved to another table to help P4 to finish his work. The instructor via the MRP checked P4 and P1's work and told them "good job"*).

While the protocol was similar, its details differed as a result of the indirect presence by MRP. We characterized MRP movement as conscious and deliberate where the instructor had to examine their visual surroundings first and decide on immediate short bursts of action for travel. We saw this in cases where the MRP instructor needed to negotiate with the table space in the classroom before moving (e.g., *The MRP instructor re-positioned the camera to visually inspect the classroom from its current perspective. Based on this scan, the MRP instructor determined a path to avoid collision with nearby tables and student participants.*)

Another example is how the MRP moves in relation to students. We observed cases where the MRP adjusted activities such as looking over the shoulder of a student, by situating the MRP to the front of the desk (e.g, *The MRP instructor wanted to check on the students' progress of their windmill. The instructor would position it near the desk, slowly rotate itself at the table's corner, moving the MRP forward, and finally rotating itself facing the table. The instructor would then rotate the camera down to examine the students' current work.*).

7 DISCUSSION: IMPLICATIONS FOR DESIGN

Hands-on physical interaction with materials supports students to understand core concepts in Making. From our study findings, we derive below a series of design guidelines **([DG])** for future MRP designs.

7.1 Support for Student Perception of MRP:

During the robot condition of the workshop, we saw students habituate to the MRP in stages. First, the MRP was regarded as a novel sight. Eventually, students' perception of the MRP adapted as they became used to how the MRP moved and developed a model of interaction as they developed familiarity with the distant instructor. MRPs have been successful in providing an approximation of presence for distant participants, however, improvements can be made in how participants perceive the distant instructor. This leads us to our first design principle, **DG-I:** ***Care should be taken to how the MRP may be physically embodied so to support student's perception and interaction with the remote teacher***.

Research could address different physical representations of the MRP, similar to avatar representations research being done in the virtual space. For example, Pejsa et al [41] described an approach to telepresence systems that uses 3D capture of its users via color and depth to create a life-size virtual representation of its users, thus creating the illusion of physical presence of the remote user. An approach like this would allow the students to perceive and interact with the distant teacher in ways similar as if the teacher was physically present.

7.2 Support for Instructor Awareness of Space:

While the instructor as MRP was able to engage students in the workshop, we observed instances where there was confusion in dialog or communication breakdown. This could be attributed to technical limitations in due to the field-of-view of the MRP camera. For instance, Johnson et al. found that wider field-of-view leads to greater performance of the MRP driver [24]. A design guideline then is that **DG-II:** ***sensory augmentation of the MRP such as widening the field-of-view can facilitate communication between instruction and students*** .

An approach to sensory augmentation of an MRP can be, for example, the use of 360 panoramic cameras. These have been studied in MRPs [24] and have shown performance increases in comparison to other camera types. In addition, such a setup could incorporate a 3D audio capture device to approximate the hearing capabilities of a physically present instructor, allowing them to perceive where a specific sound utterance (e.g., a question from a student positioned behind the instructor) is coming from. Another approach, similar to the multi-room camera setup in Smith and Skandalis [59], can consist of an additional, room-wide camera that serves to augment the remote instructors' perception of their mobile space. In addition, support staff could help to support the MRP, acting as a confederate in certain physical tasks, similar as seen in Johnson et al's study on situating room wide view for the robot view [24].

7.3 Support for Instructor Multimodal Coherence:

In Maker-based learning, physical explanations are needed to support concrete design and engineering concepts as understood by the instructor and then the student. Hall and Stevens examined this in their work on how individuals engaged in embodied communication of engineering and mathematical concepts, by observing student-tutor interactions in understanding Cartesian coordinate systems to detailed discourse analysis of civil engineer's redesign of a roadway for a housing renewal projects [17, 61]. Such embodied communication was challenging to perform through the MRP, in that while the students could observe the distant instructors' hand gestures, they were not situated in a shared space where the physical motions and expressions in explanation could take place between the teacher and student. Concepts in multimodal coherence, as explained in the related work section, best explains how multimodal coherence takes place in physical explanations, for example, Randi Engle's origo and the role of gaze and gesture in discourse coordination. The MRP, at present, does not possess a strong enough means to realize multimodal coherence, save for any gaze and gesture that can be seen in from the screen attached to the pan-tilt head of the MRP. A design guideline thus is that **DG-III:** ***Support must be designed in the MRP to embody the different ways that information can be visually communicated such as through gaze and gesture***.

There is prior work in how multimodal coherence can be supported in MRPs. Paulos and Canny's MRP seminal design featured a robot arm that enables interaction in remote spaces [40]. Later MRP designs dispensed with the arm, likely out of safety concerns. With currently available set of technologies, augmented reality (AR)-based solutions may be able to provide support for the spatially-oriented discourse we identified as a requirement for hands-on telepresence instruction. By enabling virtual augmentation of real-world objects and environments, AR is able to provide contextual information for learning across a range of subject areas like mathematics, physics, science, geography, engineering, and language arts [13, 25]. The goal of using AR to support telepresence hands-on instruction would be to enable students to see an instructor's spatial structuring gestures [43, 44] within the students' space.

7.4 Support for MRP Control and Traversal

We saw that MRP traversal differed from co-present traversal, where the activities such as scanning the classroom for status and moving to a particular point is a conscious activity, requiring precise controls to position and correct for traversal towards an intended point. Following from our observations, we provide a final design guideline, **DG-IV:** ***The MRP should allow the instructor to easily obtain a quick awareness and to focus on target students and spaces rather than interaction mechanics of navigation maneuvers***.

Many different approaches can be researched to improve MRP classroom traversal. For example, the pan-tilt head on the MRP can be improved to provide greater degree of freedom so the driver can scan about the x and y axis without resorting to first turning the MRP as a whole to the side and then readjusting the view for focus. Similar to Smith and Skandalis use of a multi-room camera setup, an approach can also be to integrate multiple MRP units such that they each cover different different rooms or different spaces. Switching quickly between the MRPs would then allow the instructor to quickly shift across far ranges of the work space. Digitally represented activities, like the ones utilizing TinkerCAD in our workshops, can be connected to the distant instructors' stream, enabling them to switch across the students' screens as they desire or as requested by students for troubleshooting. And yet another approach could be to preload in the MRP system the location of each student in the classroom based on a seat map. The focus of the instructor would then be to indicate which student he or she wants to move to, and the system would automatically calculate optimal pathways to that student and move the MRP accordingly.

8 CONCLUSION

Our study identified and characterized differences between CP and MRP representations in supporting distant Maker-based learning in a simulated classroom setting. A main limitation of the study was that it was a one-shot study done in an informal setting (a classroom setting was simulated but the study was still conducted as a workshop). In addition, the study did not account for student adaption to technology over time (e.g., the instructor becomes familiar enough with driving the MRP overtime so that navigation becomes automatic where the mechanics of driving becomes less of a distraction from classroom awareness). Thus, while we saw differences in student outcomes like design self-efficacy between the post- and the pre-study scores, we did not see any impact on the students' Maker Mindset. Furthermore, our sample size is small for quantitative analyses, even though we used non-parametric tests. However, our study did provide ample data for qualitative analysis that enabled us to derive useful implications for design. Future work will investigate different ways to augment an MRP for hands-on distance instruction based on the design guidelines presented in this paper, and examine differences across co-present instructors, existing off-the-shelf solutions (e.g., existing MRPs and video teleconferencing applications), and custom augmented MRPs.

There is a pressing need to provide rural and remote students with a hands-on technology experience and access to STEM expertise. This paper addressed the challenge of supporting such distance hands-on learning where the instructor needs access to the student's physical space in the distant classroom. We presented a laboratory study that informs how distance hands-on instruction may be mediated through the use of mobile telepresence robot platforms. Our results show the potential of MRPs to support distance hands-on learning, but also and more importantly, highlighted the need to design future MRPs to account for MRP physical representation, space awareness, multimodal coherence, and control and traversal.

9 SELECTION AND PARTICIPATION:

Children who participated in the workshops were selected through a self-selected pool of high school students. Interested students and their parents were given informed consents issued by the researchers' university IRB. Informed consent states explicitly that audio and video recorded data would be collected. Students for the pilot Maker Colonias program participated in the study as part of a high school technology course credit.

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