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Application of Phone-Based Robotic Arm Teleoperation in Remote Hands-On Labs for Engineering Education

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Abstract

Remote education, particularly in manufacturing engineering disciplines, is often limited in providing authentic hands-on learning experiences. Teleoperation has shown its potential to bridge this gap, yielding gains in fidelity, accessibility, and flexibility. However, traditional systems rely on expensive input devices that require significant training – such as space mice or virtual reality equipment. These devices restrict the broader adoption in education. To address these challenges, we developed and implemented TeleopLab: intuitive teleoperations to enable accessible remote hands-on labs. TeleopLab allows students to remotely control a robotic arm and lab equipment in real time using a smartphone motion interface in conjunction with Zoom. We designed TeleopLab to preserve the interactivity and real-world complexity of this process while transitioning the lab to an online format with minimal modification to the original lab content. This system was implemented in a professional laboratory course in an industry-led advanced manufacturing training program at an innovation center in western Massachusetts. This program includes complex tasks such as testing the tensile strength of 3D-printed parts. Students must iteratively use the results of the tensile strength measurement to adjust the 3D printing parameter settings and improve the quality of the print through multiple cycles. TeleopLab preserves the interactivity and real-world complexity of these processes, allowing students to conduct multiple cycles of testing and adjustment critical to manufacturing training. The educational impact of TeleopLab was evaluated using the Motivated Strategies for Learning Questionnaire (MSLQ), with pre- and post-use data collected from six students. The results showed an improvement of 25% in self-efficacy, 27% in motivation to re-engage, and a reduction of 13% in fear of making mistakes among students during the lab activities. Our findings suggest that TeleopLab offers a scalable, cost-effective solution to support authentic and interactive hands-on learning for remote learners.

Keywords: Teleoperation, Remote Learning, Remote Lab, Accessibility

1 Introduction

In recent years, remote and hybrid learning has experienced an unprecedented boom across various levels of education [1–6]. Stimulated by advances in digital communication tools [7, 8] and accelerated by global circumstances necessitating flexible teaching approaches [9–12], this shift has broadened access and extended learning opportunities worldwide. Yet, engineering educators face a critical challenge when attempting to replicate hands-on experiences [10, 13], particularly in manufacturing programs where iterative experimentation, physical manipulation of equipment, and real-time data collection are essential [14–18].

Among the emerging solutions for remote labs, simulation-based platforms have garnered attention for their wide accessibility and relatively low setup costs. These virtual environments enable students to practice and visualize engineering concepts without geographic or scheduling constraints. However, although simulations can effectively reinforce theoretical knowledge, they often lack the physical realism and unpredictability of authentic lab work [19–23]. Updating or expanding simulation environments to reflect changing industrial practices can also be expensive and time-consuming. Such limitations have led educators to explore teleoperation systems, which offer the promise of direct interaction with physical equipment from a distance.

Several studies have investigated the application of teleoperation in educational settings. Certain systems have been developed to utilize the inherent connection between teleoperation and robotics, aiming to instruct on robotic concepts like navigation [24] or robot control [25–27]. Meanwhile, other systems broaden the scope of teleoperation to a wider array of disciplines that can gain from remote control capabilities, including material science [28, 29], manufacturing [30, 31], chemistry [32], and mechatronics [33].

Despite the potential of teleoperation, many platforms rely on traditional input devices, like standard mice and keyboards [24, 25, 27, 28, 30–32, 34], or specialized hardware, such as virtual reality headsets [34–37] and haptic controllers [37–41]. These options do not fully address the need for intuitive interaction for realistic remote interactions: traditional devices lack the fidelity and ergonomics to manipulate complex, real-world tasks effectively [42], while specialized systems often carry prohibitive costs [43–45] and demand steep training curves [45–47]. As a result, instructors are sometimes pressured to dilute or restructure lab activities to fit these constraints, ultimately eroding the iterative, hands-on processes essential for robust manufacturing education. Without these genuine cycles of trial, feedback, and refinement, students may struggle to transition seamlessly from conceptual understanding to real-world application, undermining a cornerstone of practical engineering training.

To address these issues, we developed TeleopLab, a remote-laboratory system that omits expensive or specialized hardware in favor of a standard smartphone interface and a common video-conferencing platform (Zoom) (Fig. 1). This design lowers the financial and logistical barriers typically associated with teleoperation (i.e., off-site control), allowing students to control robotic arms and other lab equipment in real time with minimal disruption to existing lab curricula. While our previous work details TeleopLab's technical architecture, the current study focuses on how TeleopLab enables iterative, high-fidelity learning experiences in a remote environment. By maintaining the core elements of traditional lab exercises—setup, manipulation, measurement, and troubleshooting—TeleopLab preserves the essential richness and complexity

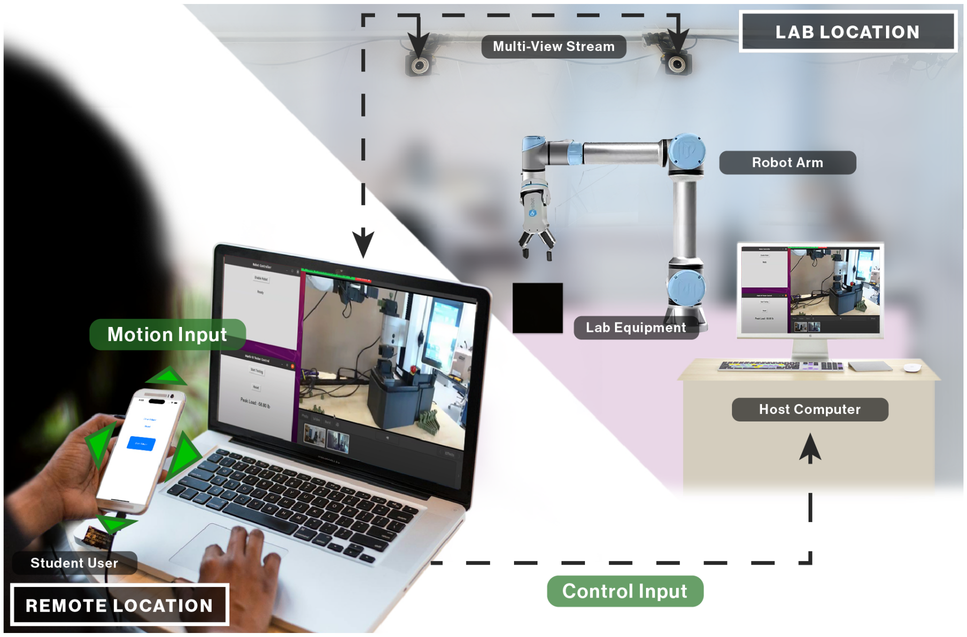

Figure 1: **TeleopLab System Setup.** The user manipulates the robot by maneuvering their phone to set waypoints and manages the lab equipment via Zoom's remote control feature on the host computer. Camera feeds are sent to the host computer and shown on the remote desktop for the user to observe.

that shape professional manufacturing practice.

Through this approach, TeleopLab merges the accessibility of simulations with the reality of physical experimentation, targeting a long-standing obstacle in remote engineering education: delivering truly hands-on practice without incurring prohibitive costs. In the sections that follow, we situate TeleopLab within the broader landscape of remote manufacturing education, describe its application in a professional advanced manufacturing course, and discuss the system's impact on learner engagement, motivation, and outcomes. Our findings point to a cost-effective, user-friendly path forward for institutions and training programs seeking to balance flexible access with the experiential rigor demanded by modern manufacturing curricula.

2 Methods

2.1 System Setup

TeleopLab consists of two main components—the teleoperation station and the user endpoint—as shown in Fig. 2. On the station side, a robotic arm, an adaptive gripper, two cameras, a host computer, and a tensile testing machine enable real-time remote experimentation. On the user side, a smartphone app and a second device for Zoom provide a streamlined interface for controlling the station and viewing lab operations.

2.1.1 Teleoperation Station

- **Robotic Arm:** We used an ABB-IRB120 arm with an IRC 5 controller. The arm, released in 2010, was selected to ensure compatibility across various educational and industrial contexts. The Robot Operating System (ROS) Noetic (Ubuntu 20.04) manages motion. While ABB's ROS Industrial driver uses a TCP-based Robot Web Service (RWS) unsuited for high-frequency teleoperation, we implemented a Google Protocol Buffers (UDP)-based Externally Guided Motion (EGM) control [48] for smoother, real-time performance. Aside from collision-error acknowledgment, all robot settings are configured remotely, reducing the need for onsite operation on the robot controller/pendant.

- **Gripper:** An InstaGrasp adaptive gripper [49] provides versatile, cost-effective manipulation. It is 3D printed with PLA and TPU, making it easy to replicate and maintain in educational settings where students handle varied objects.

- **Cameras:** Two cameras (Fig. 3) give students multiple perspectives. A RealSense D405 3D camera is mounted on the robot's end effector for close-up views of manipulation tasks, while a Logitech C920x HD Pro Webcam on a tripod offers a wide-angle overview. Both streams are shared via Cheese on Ubuntu, enabling smooth switching in Zoom.

- **Host:** An HP EliteBook 840 laptop (i5-4300U, 8GB RAM) running Ubuntu 20.04 as the primary OS serves as the system's core, handling user inputs, robot controls, and tensile tester commands. The motion commands sent from students' phones are converted to robot poses by a teleoperation robot interface [50], and to robot joint angles by TracIK [51]. A lab equipment interface controls a Mark-10 F305-EM tensile tester via serial communication. Students initiate and reset tensile tests through a simple, clickable UI (Fig. 2). For lab equipment that lacks external control capabilities or automation features, using robotic arms for direct manipulation or integrating additional automation systems may be considered as possible solutions.

2.1.2 User Endpoint

- **Smartphone App:** Students operate the robot using an iOS or Android app (Fig. 4) built on ARKit (Apple) or ARCore (Google), which translates phone motion into robot commands. Tapping "start teleop" sets a relative origin, simplifying extended manipulations. A single button controls the gripper (open/close), and another resets the robot to a neutral position. The app connects automatically to the host computer using a hard-coded IP and port. The APPs were designed to cover a wide range of devices with Android 7.0 and iOS 11 as the minimum requirements, respectively.

  Motion sensing performance varied depending on the phone model. Lidar-capable iPhones achieved sub-centimeter accuracy, benefiting from dedicated depth sensors that enable more precise measurements. In contrast, other phones—including many Android devices generally delivered accuracy at the centimeter level.

- **Remote Desktop:** A second device (e.g., laptop, tablet) connects to Zoom to view the robot's workspace, switch between the close-up and wide-angle cameras, and access the desktop running the robot and tensile tester interfaces.

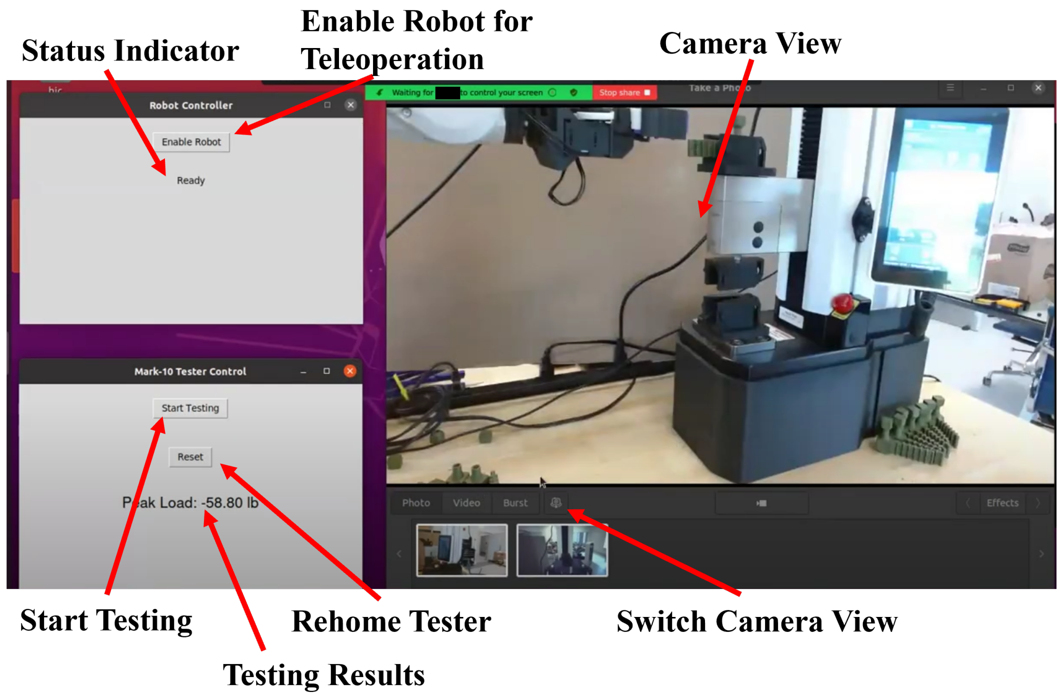

Figure 2: **Teleoperation Station User Interface.** The interface has three components: (1) UI for teleoperation (upper left), (2) UI for lab equipment operation (lower left), (3) camera views (right)

2.2 User Testing

A user testing was conducted to evaluate the usability and effectiveness of TeleopLab in lab-centric remote learning, especially in terms of learner preferences, learner experiences, and cognitive outcomes. The study involves the development of learning materials, training materials, pre- and post-surveys, and optional interviews. The study was designed so that everything could be completed remotely.

2.2.1 Study Context and Participants

This study was conducted in a workforce training program during Summer 2024 at an innovation center in western Massachusetts. This lab-based course centers on advanced manufacturing topics, including the DMAIC (Design, Measure, Analyze, Improve, and Control) problem-solving framework, design of experiment, manufacturing variance, and statistics, and emphasizes high-fidelity experience with real-world industrial problems.

The program, now in its third iteration, had previously hosted two cohorts that were conducted entirely in person. However, for the third cohort, the laboratory component was shifted to a purely remote format to accommodate the geographic dispersion of participants. For this third cohort, the main educational goal remained consistent—teaching process optimization and iterative experimentation—but the hands-on lab portion was adapted to TeleopLab's remote platform to replicate essential in-person experiences from past cohorts.

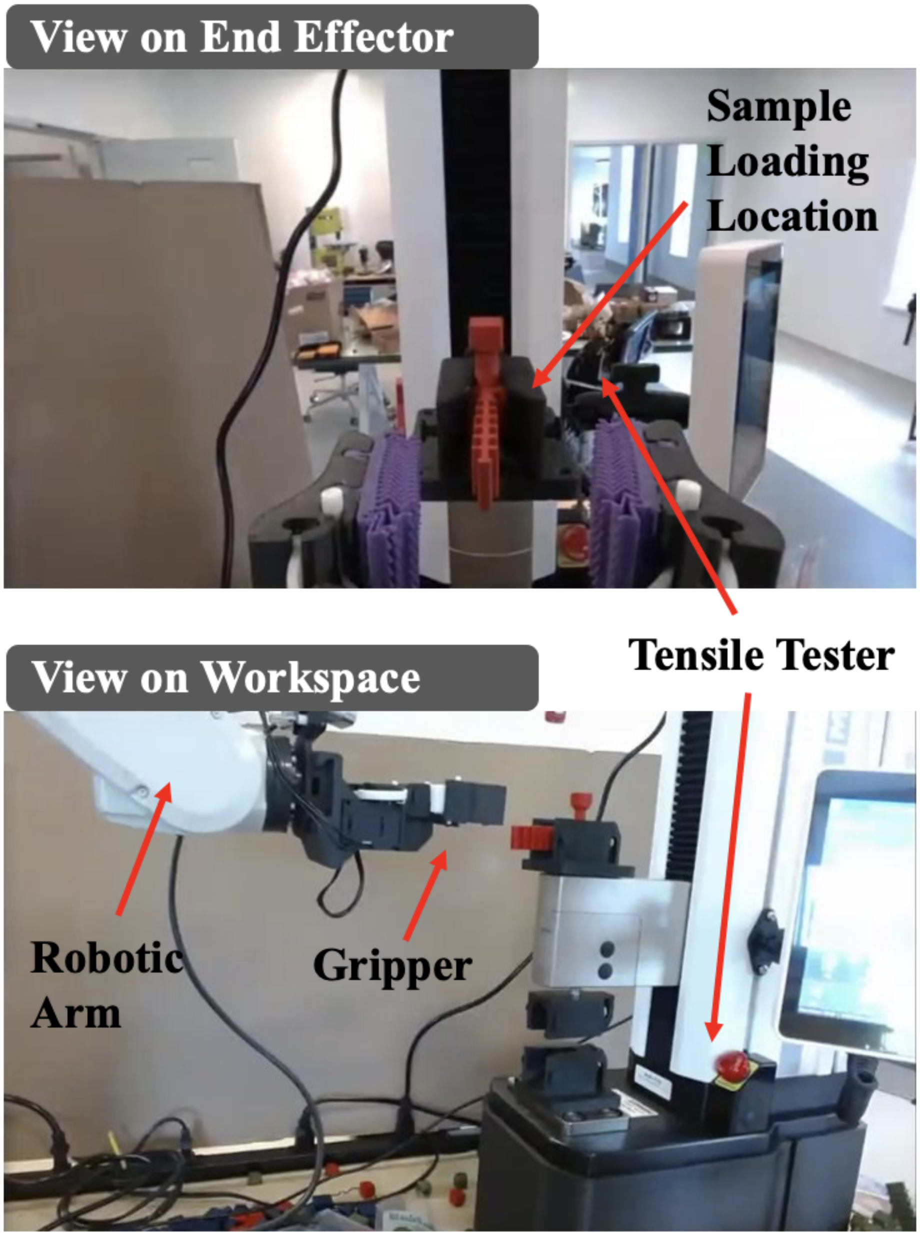

Figure 3: **Camera Views.**

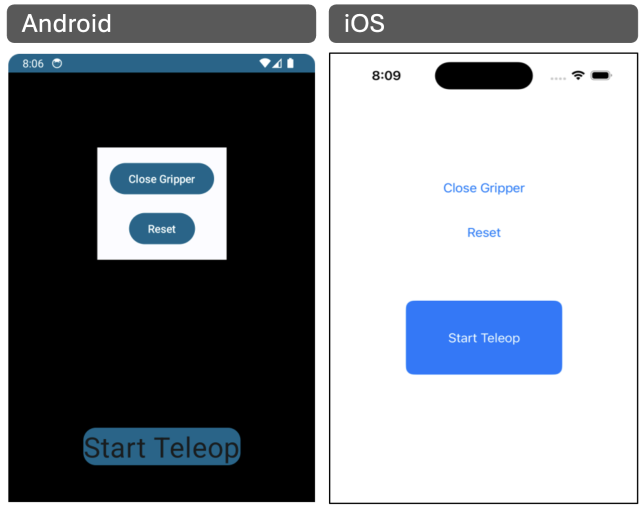

Figure 4: **Android and iOS APP.** The gripper button is responsible for operating the gripper's opening and closing functions. The reset button directs the robotic arm to return to its default home position. Holding down the "Start Teleop" button initiates the transmission of motion inputs.

Over the course's six-week duration (four hours per week), three weeks were devoted to lab activities focused on optimizing production parameters for a 3D-printed part. Specifically, students aimed to reduce print times while maintaining the highest possible tensile strength. In the previous, fully in-person setup, students were first given several batches of baseline parts—each with known printing parameters—to measure and evaluate. Based on these initial test results, they proposed revised printing parameters in an effort to shorten production times without compromising quality. After fabricating new parts with the updated parameters, students repeated the tensile tests to determine whether the results aligned with their predictions. Finally, they performed one last round of parameter adjustments and tests, selecting and presenting the optimal set of parameters that offered the best balance between reduced printing time and mechanical strength.

The cohort primarily consisted of incumbent workers, engineers, and managers from diverse professional backgrounds. Participants had educational backgrounds ranging from high school diplomas to bachelor's degrees, and represented a wide age spectrum. While many had limited exposure to robotic teleoperation, the program incorporated concise, focused training sessions to acquaint them with essential teleoperation knowledge and skills. These brief sessions ensured that participants could master the basics without diverting undue time and attention from the main learning objectives.

2.2.2 Study Procedure

At the beginning of the cohort, we adapted our existing course materials for a fully online format. Direct adaptation involved converting the original problem statement, experiment design principles (following a DMAIC framework), and data analysis instructions into handouts or recorded videos, which were then uploaded to the learning management system (LMS). Modification entailed reconfiguring the in-person lab activities to an online setting while retaining as many physical, hands-on elements as possible. The redesigned lab task ensures that students maintain active engagement with tangible equipment via teleoperation, following these steps:

1. Connecting to the TeleopLab server using their smartphone app
2. Remotely controlling the robotic arm to pick up a specimen
3. Positioning the specimen on the Mark-10 tensile tester
4. Operating the tester to measure tensile strength and record data
5. Returning to the reloading location to repeat the process with a new specimen.

Alongside these lab instructions, a concise lecture on teleoperation and robotics was developed to give students foundational knowledge, motivation, and context for interacting with the system remotely.

The 10 students participated in the lab session. However, three of them had the phone older than the minimum requirement and one of them did not complete the study, resulting 6 students completting the study. Each student was asked to complete a survey with pre- and post-assessments. The assessment contain 5 parts: (1) biographical information (2) Motivated Strategies for Learning Questionnaire (MSLQ) [52], (3) expectation vs. experience, (4) overall rating of the experience, and (5) free response feedback.

A total of ten students initially enrolled in the remote lab sessions, but due to hardware incompatibilities (three participants owned phones below the minimum technical requirements) and one participant failing to finish the study, six students ultimately completed the full laboratory experience. For the three students, a keyboard-based teleoperation program was provided as an alternative to help them finish. Each participant was required to fill out a survey with pre- and post-assessments, comprising four sections: (1) biographical information, (2) Motivated Strategies for Learning Questionnaire (MSLQ) [52], (3) overall rating of the experience, and (4) free-response feedback. This multi-part assessment captured not only baseline traits and motivational factors but also students' evolving perspectives on TeleopLab's remote, hands-on learning components.

3 Results and Discussions

3.1 MLSQ

Table 1 presents the pre- and post-self-report ratings for each participant (S1–S6) across four main categories—Self-Efficacy (SE) in Learning, SE in Application, SE in Performance, and Fear of Mistakes—as well as Motivation to Re-engage. The rows are grouped by category rather than question order, making it easier to spot patterns within each dimension of learning. Each response is color-coded according to the numeric rating on a 5-point Likert scale, where red (1) indicates Strongly Disagree and green (5) indicates Strongly Agree.

- **Self-Efficacy (Learning):** The questions focus on students' self-efficacy toward learning. Most students' ratings shift toward greener cells from pre to post, suggesting they grew

Table 1: Reordered MSLQ Items (Q1–Q15) by Category with Pre/Post Ratings (1 = Strongly Disagree, 5 = Strongly Agree).

		Pre Ratings						Post Ratings					
Q#	**Category**	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**
Q1	SE (Learning)	3	4	4	3	4	5	4	5	5	4	5	5
Q5	SE (Learning)	4	3	4	3	4	1	4	5	5	4	4	4
Q9	SE (Learning)	4	4	3	4	4	4	3	5	4	5	4	5
Q2	SE (Application)	3	3	4	3	4	2	3	4	5	4	5	4
Q6	SE (Application)	4	3	4	3	3	1	3	4	5	5	4	4
Q10	SE (Application)	3	2	5	2	5	4	4	5	5	5	5	5
Q3	SE (Performance)	4	4	4	4	3	5	3	5	5	5	4	5
Q7	SE (Performance)	4	4	4	4	3	4	4	5	5	5	4	4
Q11	SE (Performance)	5	3	4	3	4	4	4	5	5	5	4	5
Q4	Fear of Mistakes	3	2	2	5	5	3	4	4	5	5	5	5
Q8	Fear of Mistakes	5	4	5	5	4	4	5	4	5	5	5	5
Q12	Fear of Mistakes	4	5	5	5	5	5	4	5	5	5	5	5
Q13	Motivation (Re-engage)	5	5	4	3	4	4	5	5	5	5	4	5
Q14	Motivation (Re-engage)	3	4	3	3	4	4	4	5	5	3	3	5
Q15	Motivation (Re-engage)	3	4	1	3	3	2	4	5	5	3	3	5

more confident in their ability to learn the course material.

- **Self-Efficacy (Application):** These items gauge how prepared students feel to apply what they have learned. In general, the post ratings are higher (more green), demonstrating increased self-assuredness in carrying out manufacturing processes or teleoperation tasks.
- **Self-Efficacy (Performance):** This category reflects confidence in achieving high performance on specific lab tasks or objectives. Similar to the other SE measures, the table shows that most participants reported stronger agreement (moving from yellows and light greens to darker greens), suggesting they felt increasingly capable of meeting performance benchmarks.
- **Fear of Mistakes:** These items assess anxiety about errors or damaging equipment. Notable improvements appear here as well, with participants shifting from lower to higher ratings.
- **Motivation to Re-engage:**

  In this final category, the majority of cells shift from lighter to darker greens, reflecting a greater willingness to continue learning or to repeat the lab experience. Students generally express higher post-lab motivation, possibly due to the hands-on teleoperation aspect of the course.

Table 2 summarizes the overall percentage improvements from pre- to post-assessment for each

MSLQ category and for Motivation to Re-engage. Specifically, the data show how students' self-reported ratings changed on a 5-point Likert scale before and after participating in the teleoperated lab activities. Participants' confidence in their ability to learn and understand manufacturing concepts showed a moderate 23% gain. This suggests that direct engagement with physical lab equipment—although remotely—helped clarify theoretical knowledge and boosted learners' perceived competence. The most substantial rise (36%) was in applying learned skills to real tasks. Operating the robotic arm and tensile testing machine in real time may have helped students see concrete cause-and-effect relationships, thereby strengthening their belief in their practical abilities. A 17% improvement indicates that while students felt more assured in meeting performance benchmarks, this rise was more modest compared to other self-efficacy measures. Hands-on tasks may have involved steep learning curves, especially for those unfamiliar with robotic teleoperation. A drop of 13% in fear or anxiety around making errors suggests students became more comfortable experimenting, likely thanks to the system's user-friendly interface, virtual fences, and staff support. Lower anxiety typically correlates with higher willingness to explore and learn. A notable 27% increase in students' desire to continue or repeat lab-based activities underscores the role of active participation in building enthusiasm. The novelty of controlling physical equipment from afar, combined with tangible feedback, likely contributed to sustained interest.

Table 2: Percentage Improvements by Category with Pre- and Post-Assessment Data

Category	**Pre (Mean ± SD)**	**Post (Mean ± SD)**	**Improvement (%)**
Self-efficacy (Learning)	3.61 ± 0.85	4.44 ± 0.62	23%
Self-efficacy (Application)	3.22 ± 1.06	4.39 ± 0.70	36%
Self-efficacy (Performance)	3.89 ± 0.58	4.56 ± 0.62	17%
Overall Self-efficacy	—		25%
Fear of Mistakes	4.22 ± 1.06	4.78 ± 0.43	13%
Motivation to Re-engage	3.44 ± 0.98	4.39 ± 0.85	27%

The percentage gains in MSLQ underline the positive impact of integrating real-time teleoperation into a remote lab environment. The largest jump—Self-Efficacy (Application)—suggests that when students can manipulate physical hardware from a distance and witness immediate outcomes, they form stronger convictions about their ability to apply theoretical concepts. Meanwhile, Fear of Mistakes shows a moderate yet meaningful decline, implying that an accessible, well-supported teleoperation interface can help novices feel safer experimenting.

Notably, Motivation to Re-engage rose by over 27%, which indicates that experiential, real-time engagement can mitigate some of the disconnect often reported in remote learning contexts. By contrast, Self-Efficacy (Performance) had a smaller upswing than Application, possibly pointing to lingering uncertainties about mastering complex robotic tasks within limited session time. Future designs could incorporate additional practice or scaffolding to further bolster performance confidence.

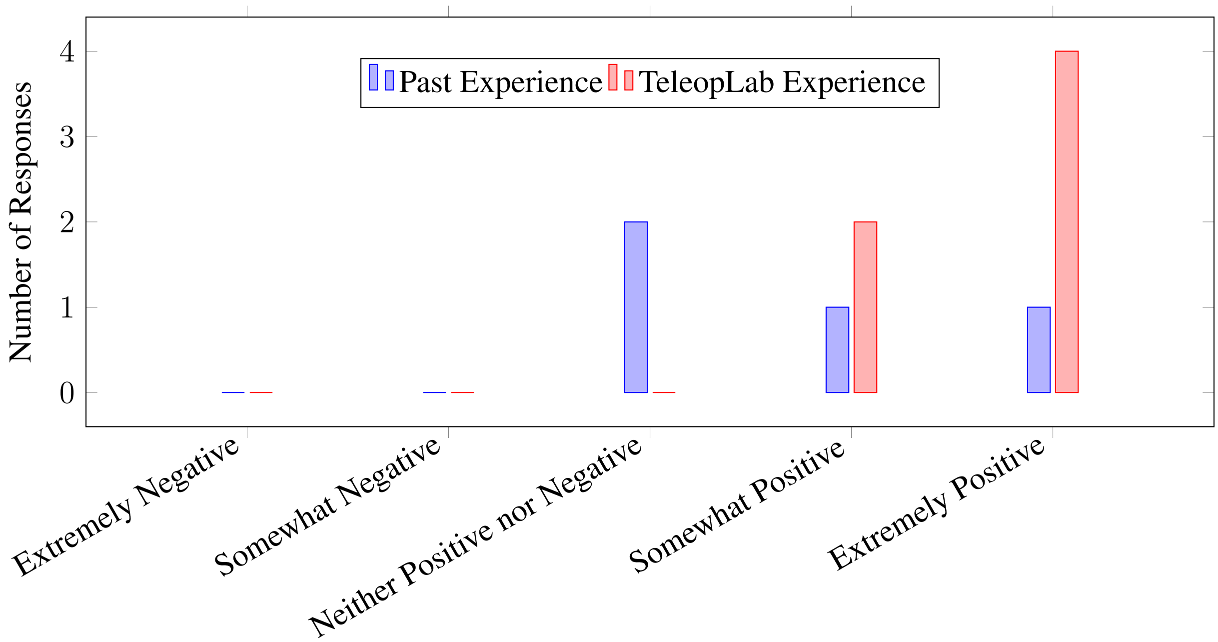

Figure 5: **Comparison of Learning Experience Ratings.**

3.2 Overall Experience

Among the six students, four had previously engaged in remote learning (Fig. 5). Two students previously rated past experience as "Neither Positive nor Negative," one student as "Somewhat Positive," and one as "Extremely Positive." By contrast, for their experience with TeleopLab, two students reported "Somewhat Positive," while four selected "Extremely Positive." This distribution shows a clear shift from more neutral or mildly positive perceptions in the past to strongly positive attitudes in the present, suggesting that the current learning setup was better received overall.

3.3 Qualitative Feedback

In addition to the quantitative metrics, students provided open-ended feedback highlighting both the positive aspects of TeleopLab and suggestions for improvement, such as:

- "Color-coded alerts on the controller app to show proximity to the target would be extremely helpful."
- "It was very helpful with the data collection and a very good experience."
- "It was an interesting experience and enjoyed doing it"
- "There were 'bugs' in the system, such as disconnecting and needing to reconnect and needing to restart the software numerous times, no control over full operation such as picking up dropped pieces, "finger" could have been better designed."
- "it was great! it offered a very unique experience that allowed me to work this project remotely with a hands on type experience."

- “It didn’t distract me from learning. On the contrary, I think it aided in learning.”

Overall, participants appreciated having the opportunity to experience real-time manipulation of physical lab equipment from a remote location—an experience many of them had never encountered in prior online courses. However, several areas emerged where TeleopLab could be enhanced.

Although TeleopLab successfully demonstrated remote teleoperation, periodic network glitches undermined the smoothness of the robot’s movement. Students reported instances where the robotic arm would shake or stall due to packet losses, or the session would drop entirely and require manual reconnection. For larger-scale deployment, a more robust network implementation that offers automatic, low-effort reconnection would alleviate interruptions and maintain student engagement.

Another prominent challenge was task perception when switching between two distinct camera views. While the dual-camera setup helped mitigate the lack of depth information from a single viewpoint, participants found toggling between close-up and wide-angle perspectives mentally taxing. A more integrated approach—potentially incorporating 3D rendering or augmented visualization—could reduce cognitive load and improve depth perception, thereby enhancing users’ overall sense of immersion and control.

These findings underscore the potential of TeleopLab to deliver immersive, hands-on experiences while also pointing toward concrete areas for future development. By refining network stability, streamlining reconnection protocols, and improving visual cues for remote manipulation, TeleopLab can become more robust and user-friendly in broader educational contexts.

One of the primary limitations of this study is the small sample size of six participants, which may limit the generalizability of our findings. Because the sample was limited to six participants, the results may not reflect the broad range of perspectives and experiences of all potential end-users. Despite the limited number of participants, the study provided in-depth qualitative feedback that helped us identify critical usability issues and user preferences.

4 Conclusion

In conclusion, TeleopLab demonstrates substantial promise for delivering authentic, hands-on learning in remote engineering education. By integrating a cost-effective smartphone interface with real-time robotic control, TeleopLab preserves the interactivity and experiential rigor typically found in physical labs—without the expense or logistical constraints of specialized hardware. The system’s ability to enhance self-efficacy, motivate learners, and reduce anxiety around making mistakes underscores its advantage over purely simulated approaches. Nonetheless, challenges such as network reliability, camera-view management, and depth perception remain areas for refinement. Future improvements—ranging from robust auto-reconnection protocols to more sophisticated remote 3D visualization—will further strengthen TeleopLab’s effectiveness and scalability. Beyond manufacturing contexts, TeleopLab holds the potential to transform how students and professionals across STEM disciplines engage with real-world equipment and processes, bridging physical distances and fostering the practical skills essential for career success.

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References

[1] Tahsin Ciloglu and Ahmet Berk Ustun. The effects of mobile ar-based biology learning experience on students' motivation, self-efficacy, and attitudes in online learning. *Journal of Science Education and Technology*, 32: 309–337, 6 2023. ISSN 15731839. doi: 10.1007/s10956-023-10030-7.

[2] Naomi T. Fitter, Nisha Raghunath, Elizabeth Cha, Christopher A. Sanchez, Leila Takayama, and Maja J. Mataric. Are we there yet? comparing remote learning technologies in the university classroom. *IEEE Robotics and Automation Letters*, 5:2706–2713, 4 2020. ISSN 23773766. doi: 10.1109/LRA.2020.2970939.

[3] Li Gao. Contemporary american literature in online learning: fostering reading motivation and student engagement. *Education and Information Technologies*, 28:4725–4740, 4 2023. ISSN 15737608. doi: 10.1007/s10639-022-11329-5.

[4] Heather MacNeill, Ken Masters, Kataryna Nemethy, and Raquel Correia. Online learning in health professions education. part 1: Teaching and learning in online environments: Amee guide no. 161. *Medical Teacher*, 46: 4–17, 2024. ISSN 1466187X. doi: 10.1080/0142159X.2023.2197135.

[5] Seni Susanti, Riki Purnama Putra, Rena Denya Agustina, Nguyen Phu Quy, Hariman Surya Siregar, and Jose da Silva. Exploring the educational landscape: The impact of post-covid online learning on physics education undergraduates' academic engagement and achievement. *Indonesian Journal on Learning and Advanced Education (IJOLAE)*, 6:86–104, 12 2023. ISSN 2655-920X. doi: 10.23917/ijolae.v6i1.22179.

[6] Milan Pokorný. Online learning in teaching initial math education. In Pradeep Kumar, Kolekar Maheshkumar H., Kar Arpan Kumar, Gonçalves Paulo J Sequeira Singh Yashwant, and Singh, editors, *Proceedings of International Conference on Recent Innovations in Computing*, pages 657–667. Springer Nature Singapore, 2023. ISBN 978-981-19-9876-8.

[7] I Calvo, M Marcos, D Orive, and I Sarachaga. Building complex remote learning laboratories. *Computer Applications in Engineering Education*, 18:53–66, 2010. doi: https://doi.org/10.1002/cae.20239. URL `https://onlinelibrary.wiley.com/doi/abs/10.1002/cae.20239`.

[8] Philip Hunter. The virtual university. *EMBO reports*, 16:146–148, 2 2015. ISSN 1469-221X. doi: 10.15252/embr.201440016. URL `https://www.embopress.org/doi/10.15252/embr.201440016`.

[9] Wahab Ali. Online and remote learning in higher education institutes: A necessity in light of covid-19 pandemic. *Higher Education Studies*, 10:16, 5 2020. ISSN 1925-4741. doi: 10.5539/hes.v10n3p16.

[10] Jing Ma and Jeffrey V. Nickerson. Hands-on, simulated, and remote laboratories: A comparative literature review. *ACM Computing Surveys*, 38:1, 2006. ISSN 03600300. doi: 10.1145/1132960.1132961.

[11] Placidius Ndibalema. The global research trends on the growth of remote learning in higher education institutions: A bibliometric analysis. *International Journal of Technology in Education and Science*, 6: 218–236, 5 2022. doi: 10.46328/ijtes.332.

[12] Heather L Schwartz, David Grant, Melissa Diliberti, Gerald P Hunter, and Claude Messan Setodji. Remote learning is here to stay: Results from the first american school district panel survey, 2020.

[13] Dominik May, Gustavo R Alves, Alexander A Kist, and Susan M Zvacek. *Online laboratories in engineering education research and practice*, pages 525–552. Routledge, 2023.

[14] Nevena Ackovska and Vesna Kirandziska. The importance of hands-on experiences in robotics courses. *17th IEEE International Conference on Smart Technologies, EUROCON 2017 - Conference Proceedings*, pages 56–61, 8 2017. doi: 10.1109/EUROCON.2017.8011077.

[15] Hui-Tzu Chang, Hsien-Hua Wu, and Yi-Ting Chang. Evaluating learning outcomes by applying interdisciplinary hands-on learning to advanced technology courses. *Innovative Higher Education*, 48:619–636,

2023. doi: 10.1007/s10755-023-09653-w. URL
https://doi.org/10.1007/s10755-023-09653-w.

[16] Saroja Dhanapal, Evelyn Wan, and Zi Shan. A study on the effectiveness of hands-on experiments in learning science among year 4 students. *International Online Journal of Primary Education*, 3:20–31, 6 2014. ISSN 1300-915X. URL https://dergipark.org.tr/en/pub/iojpe/issue/69834/1113918.

[17] Jacob Filgona, Linus K Sababa, and Joel Filgona. Effect of hands-on learning strategies on senior secondary school students' academic achievement in topographical map studies in ganye educational zone, adamawa state, nigeria. *Available (Print) International Journal of Social Science and Humanities Research*, 4:276–287, 2016. ISSN 2348-3164. URL www.researchpublish.com.

[18] Nina Holstermann, Dietmar Grube, Susanne Bögeholz, N Holstermann, S Bögeholz, and D Grube. Hands-on activities and their influence on students' interest. *Res Sci Educ*, 40:743–757, 2010. doi: 10.1007/s11165-009-9142-0.

[19] Nichole K Davis, Ryan Byrne, Raj K Gupta, Anthony Santago II, and Andreas Tolk. Formal methods for establishing simulation interoperability for military health system applications. *Military Medicine*, 189: 767–774, 9 2024. ISSN 0026-4075. doi: 10.1093/milmed/usae265. URL https://doi.org/10.1093/milmed/usae265.

[20] Ryan M McAdams and GiaKhanh Trinh. Using virtual reality–based simulation in neonatal resuscitation program training. *NeoReviews*, 25:e567–e577, 9 2024. ISSN 1526-9906. doi: 10.1542/neo.25-9-e567. URL https://doi.org/10.1542/neo.25-9-e567.

[21] G. Kortemeyer. Using virtual reality for teaching kinematics. In *Journal of Physics: Conference Series*, volume 2727. Institute of Physics, 2024. doi: 10.1088/1742-6596/2727/1/012025.

[22] Torsten Reiners, Lincoln C. Wood, Sue Gregory, Hanna Teräs, Torsten Reiners, Lincoln C. Wood, Sue Gregory, and Hanna Teräs. *Gamification Design Elements in Business Education Simulations*, pages 3048–3061. IGI Global, 7 2014. doi: 10.4018/978-1-4666-5888-2.ch298. URL https://services.igi-global.com/resolvedoi/resolve.aspx?doi=10.4018/978-1-4666-5888-2.c

[23] Helen S Farley. *Learning in Virtual Worlds: Research and Applications*. Athabasca University Press, 4 2016. ISBN 9781771991346. doi: 10.15215/aupress/9781771991339.01. URL http://www.aupress.ca/index.php/books/120254.

[24] Maria Eugenia Cabrera and John Raiti. Physical robots for teaching mobility & manipulation using ros in remote learning. In *2024 ASEE Annual Conference & Exposition*, 2024.

[25] Sergey Kondratyev, Vladimir Pikalov, Artem Muravyev, and Alexei Evseev. Smart educational robotics laboratory ecosystem for remote control of robotic manipulators through telepresence technologies. In *Proceedings - 2022 2nd International Conference on Technology Enhanced Learning in Higher Education, TELE 2022*, pages 62–65. Institute of Electrical and Electronics Engineers Inc., 2022. ISBN 9781665470070. doi: 10.1109/TELE55498.2022.9801051.

[26] Saku Pöysäri, Tero Kaarlela, Morteza Dianatfar, and Minna Lanz. Educational teleoperation platform for heavy industrial robotics as a learning environment. *13th Conference on Learning Factories, CLF 2023*, page 2023, 2023. URL https://ssrn.com/abstract=4489360.

[27] Tero Kaarlela, Halldor Arnarson, Tomi Pitkäaho, Beibei Shu, Bjørn Solvang, and Sakari Pieskä. Common educational teleoperation platform for robotics utilizing digital twins. *Machines*, 10, 7 2022. ISSN 20751702. doi: 10.3390/machines10070577.

[28] Christian Pleul, Claudius Terkowsky, Isa Jahnke, and A Erman Tekkaya. Tele-operated laboratory experiments in engineering education. the uniaxial tensile test for material characterization in forming technology. *Using Remote Labs in Education. Two Little Ducks in Remote Experimentation*, (8):323–348, 2011.

[29] TR Ortelt, A Sadiki, Ch Pleul, Christoph Becker, Sami Chatti, and AE Tekkaya. Development of a tele-operative testing cell as a remote lab for material characterization. In *2014 International Conference on Interactive Collaborative Learning (ICL)*, pages 977–982. IEEE, 2014.

[30] Claudius Terkowsky, Isa Jahnke, Roberto Licari, Per Johannssen, Gianluca Buffa, Matthias Heiner, Livan Fratini, Ernesto LoValvo, Mihai Nicolescu, Johannes Wildt, et al. Developing tele-operated laboratories for manufacturing engineering education. platform for e-learning and telemetric experimentation (petex). *International Journal of Online and Biomedical Engineering (iJOE)*, 6(5):60–70, 2010.

[31] Mauricio Hincapie, Oscar Salas, Miguel Ramirez, and B Carranza. Implementation of a teleoperated didactic manufacturing cell through internet2 as a means of engineering education*. *International Journal of Engineering Education*, 29(1):1–11, 2013.

[32] Maria C Moreno, Yerson Duvan Angulo, and Oscar J Suarez. Teleoperated robot prototype for the manipulation and transport of chemical substances in laboratory: a low-cost adaptation. In *2022 18th IEEE/ASME International Conference on Mechatronic and Embedded Systems and Applications (MESA)*, pages 1–6. IEEE, 2022.

[33] Silverio Lopez, Nicolas Perticari Pesci, and David Quintero. Adapting through a pandemic: Creating a hands-on mechatronics laboratory with team-based collaboration for remote learning. In *2022 ASEE Annual Conference & Exposition*, 2022.

[34] Qing Tan, Marc Denojean-Mairet, Hongxue Wang, Xiaokun Zhang, Frédérique C. Pivot, and Roland Treu. Toward a telepresence robot empowered smart lab. *Smart Learning Environments*, 6, 12 2019. doi: 10.1186/s40561-019-0084-3.

[35] Salvatore Livatino, Dario C Guastella, Giovanni Muscato, Vincenzo Rinaldi, Luciano Cantelli, Carmelo D Melita, Alessandro Caniglia, Riccardo Mazza, and Gianluca Padula. Intuitive robot teleoperation through multi-sensor informed mixed reality visual aids. *Ieee Access*, 9:25795–25808, 2021.

[36] Xiwen Dengxiong, Xueting Wang, Shi Bai, and Yunbo Zhang. Self-supervised 6-dof robot grasping by demonstration via augmented reality teleoperation system, 2024.

[37] Sushanta Mohan Rakshit, Subharthi Banerjee, Michael Hempel, and Hamid Sharif. Fusion of vr and teleoperation for innovative near-presence laboratory experience in engineering education. In *2017 IEEE International Conference on Electro Information Technology (EIT)*, pages 376–381. IEEE, 5 2017. ISBN 978-1-5090-4767-3. doi: 10.1109/EIT.2017.8053390. URL `http://ieeexplore.ieee.org/document/8053390/`.

[38] Claudia González, J Ernesto Solanes, Adolfo Munoz, Luis Gracia, Vicent Girbés-Juan, and Josep Tornero. Advanced teleoperation and control system for industrial robots based on augmented virtuality and haptic feedback. *Journal of Manufacturing Systems*, 59:283–298, 2021.

[39] Mahdi Tavakoli, Rajni V Patel, Mehrdad Moallen, and Arash Aziminejad. *Haptics for teleoperated surgical robotic systems*, volume 1. World Scientific, 2008.

[40] Mojtaba Esfandiari, Ji Woong Kim, Botao Zhao, Golchehr Amirkhani, Muhammad Hadi, Peter Gehlbach, and Russell H Taylor. Cooperative vs. teleoperation control of the steady hand eye robot with adaptive sclera force control: A comparative study, 2023.

[41] Nural Yilmaz, Brendan Burkhart, Anton Deguet, Peter Kazanzides, and Ugur Tumerdem. Sensorless transparency optimized haptic teleoperation on the da vinci research kit. *IEEE Robotics and Automation Letters*, 9:971–978, 2 2024. ISSN 23773766. doi: 10.1109/LRA.2023.3335779.

[42] Ajay Mandlekar, Yuke Zhu, Animesh Garg, Jonathan Booher, Max Spero, Albert Tung, Julian Gao, John Emmons, Anchit Gupta, Emre Orbay, Silvio Savarese, and Li Fei-Fei. Roboturk: A crowdsourcing platform for robotic skill learning through imitation, 2018.

[43] Narges Ashtari, Andrea Bunt, Joanna McGrenere, Michael Nebeling, and Parmit K Chilana. Creating augmented and virtual reality applications: Current practices, challenges, and opportunities. In *Proceedings of the 2020 CHI conference on human factors in computing systems*, pages 1–13, 2020.

[44] Hadi Ardiny and Esmaeel Khanmirza. The role of ar and vr technologies in education developments: opportunities and challenges. In *2018 6th rsi international conference on robotics and mechatronics (icrom)*, pages 482–487. IEEE, 2018.

[45] Sam Kavanagh, Andrew Luxton-Reilly, Burkhard Wuensche, and Beryl Plimmer. A systematic review of virtual reality in education, 2017.

[46] Manuel Fernandez. Augmented virtual reality: How to improve education systems. *Higher Learning Research Communications*, 7:1, 2017. doi: 10.18870/hlrc.v7i1.373.

[47] Carlos Efrén Mora, Av Angel, Jorge Martín-Gutiérrez, Beatriz Añorbe-Díaz, and Antonio González-Marrero. Virtual technologies trends in education. *OPEN ACCESS EURASIA Journal of Mathematics Science and Technology Education*, 13:469–486, 2017. doi: 10.12973/eurasia.2017.00626a. URL `https://www.magicleap.com`.

[48] Abb Robotics. Application manual - externally guided motion, 2019.

[49] Xin Zhou and Adam J. Spiers. Instagrasp: An entirely 3d printed adaptive gripper with tpu soft elements and minimal assembly time. In *2023 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, 5 2023.

[50] Shivin Dass, Wensi Ai, Yuqian Jiang, Samik Singh, Jiaheng Hu, Ruohan Zhang, Peter Stone, Ben Abbatematteo, and Roberto Martín-Martín. Telemoma: A modular and versatile teleoperation system for mobile manipulation, 2024. URL `https://robin-lab.cs.utexas.edu/telemoma-web/`.

[51] Patrick Beeson and Barrett Ames. Trac-ik: An open-source library for improved solving of generic inverse kinematics, 2015. URL `https://bitbucket.org/`.

[52] Paul R. Pintrich, David A. F. Smith, Teresa Garcia, and Wilbert J. Mckeachie. Reliability and predictive validity of the motivated strategies for learning questionnaire (mslq). *Educational and Psychological Measurement*, 53 (3):801–813, 1993. doi: 10.1177/0013164493053003024. URL `https://doi.org/10.1177/0013164493053003024`.

A Appendix

A.1 MLSQ Pre-Activity Questions

1. Before teleoperation sessions: I was confident I could understand the basic concepts taught in the manufacturing data collection.
2. Before teleoperation sessions: I was confident I could explain why manufacturing variation occurs.
3. Before teleoperation sessions: I expected to do well in the manufacturing data collection activity.
4. Before teleoperation sessions: I was NOT afraid that my mistakes in teleoperation would harm the equipment.
5. Before teleoperation sessions: I was certain I could understand the most challenging material presented in the manufacturing data collection.
6. Before teleoperation sessions: I was certain I could recognize common sources of manufacturing variation.
7. Before teleoperation sessions: I was confident I could do an excellent job on the tasks of the manufacturing data collection activity.
8. Before teleoperation sessions: I was NOT afraid of trying new things because of my fear of making mistakes.
9. Before teleoperation sessions: I was certain I could master the content being taught in this activity.

10. Before teleoperation sessions: I was confident in measuring samples with a tensile tester in person (non-teleoperation).
11. Before teleoperation sessions: Considering the difficulty of this activity and my skills, I thought I would do well in the manufacturing data collection activity.
12. Before teleoperation sessions: I believed that making mistakes was a natural part of the learning process.
13. Before teleoperation sessions: I looked forward to the next time I would be able to engage with manufacturing data collection.
14. Before teleoperation sessions: I saw myself engaging with manufacturing data collection for a long time to come.
15. Before teleoperation sessions: I would seek out opportunities to engage in manufacturing data collection outside of courses.

A.2 MLSQ Post-Activity Questions

1. After teleoperation sessions: Now, I'm confident I can understand the basic concepts taught in the manufacturing data collection.
2. After teleoperation sessions: Now, I'm confident I can explain why manufacturing variation occurs.
3. After teleoperation sessions: Now, I expect to do well in the manufacturing data collection activity.
4. After teleoperation sessions: Now, I am NOT afraid that my mistakes in teleoperation will harm the equipment.
5. After teleoperation sessions: Now, I'm certain I can understand the most challenging material presented in the manufacturing data collection.
6. After teleoperation sessions: Now, I'm certain I can recognize common sources of manufacturing variation.
7. After teleoperation sessions: Now, I'm confident I can do an excellent job on the tasks of the manufacturing data collection activity.
8. After teleoperation sessions: Now, I am NOT afraid of trying new things because of my fear of making mistakes.
9. After teleoperation sessions: Now, I'm certain I can master the content being taught in this activity.
10. After teleoperation sessions: Now, I am confident in measuring samples with a tensile tester in person (non-teleoperation).
11. After teleoperation sessions: Considering the difficulty of this activity and my skills, I think I will do well in the manufacturing data collection activity.
12. After teleoperation sessions: Now, I believe that making mistakes is a natural part of the learning process.
13. After teleoperation sessions: Now, I look forward to the next time I'll be able to engage with manufacturing data collection.
14. After teleoperation sessions: Now, I see myself engaging with manufacturing data collection for a long time to come.
15. After teleoperation sessions: Now, I will seek out opportunities to engage in manufacturing data collection outside of courses.