# AUGMENTED REALITY AS A TRAINING TOOL FOR COMPOSITE MATERIALS MANUFACTURING

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## ABSTRACT

Augmented reality (AR) is a promising technology to develop educational and training tools for students and workforce development. Common composites manufacturing methods, such as hand layup and vacuum bagging, can be tedious and time-consuming to teach, especially in academic settings. Consequently, the main goal of this work was to design and develop an AR training system, integrated with a research lab workstation for composite hand layup. Utilizing a HoloLens 2 headset, it guides a user through the manufacturing process while remaining hands-free and featuring remote experiential capabilities. It includes four main steps, from fabric cutting to laminate layup and vacuum bagging. Each step features mixed reality elements, such as detailed instructions with technical definitions and material safety data sheets, gaze-activated videos, movable holograms, and expandable CAD layup models with labels. An adaptable lighting system was integrated into the workstation to provide real-world, visual feedback and updates during the manufacturing process. The AR system was tested for efficacy through performance profilers and user testing. Positive feedback was received most notably for educational benefits and clarity, with room for improvement regarding comfort (respective average ratings of 95%, 75%, and 62.5%). Further improvements and research include edge detection to assist with ply positioning.

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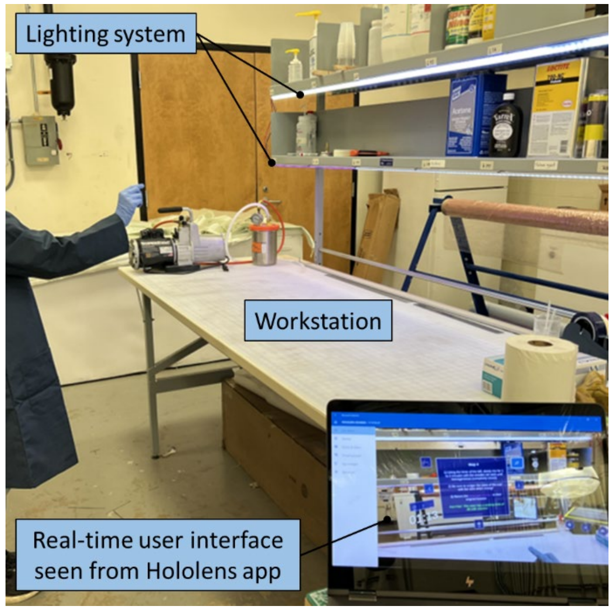
# 1. INTRODUCTION

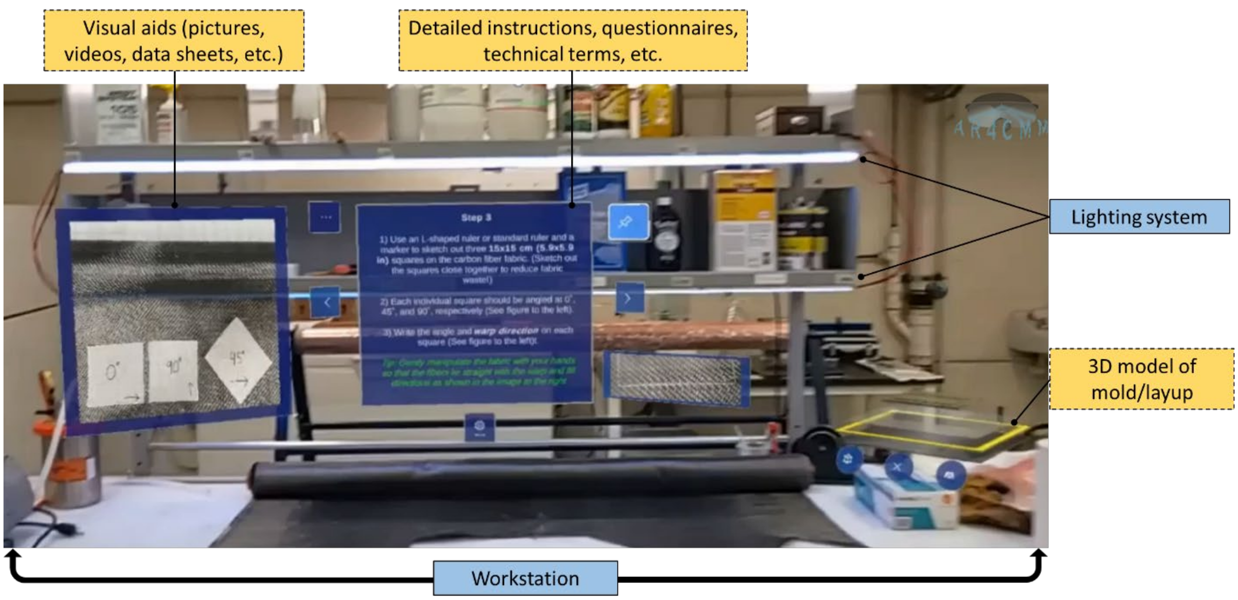
Lightweight composite materials are of great interest for applications where weight reduction is desirable. However, their manufacturing still heavily depends on manual labor in several industries. Common manufacturing methods, such as hand layup and vacuum bagging, can be tedious and time-consuming to teach, especially for wet layup of thermoset composites (TSCs) [1]. Compliance with design parameters (ply sequence, orientation, position, etc) and repeatable part quality depend on adequate personnel training. In the past years, virtual tools to assist operators during composites manufacturing and repair, such as Augmented Reality (AR), have been developed as a potential solution to improve manufacturing quality. AR is a human-computer interaction technology, which can overlay holograms (or digital mockups) onto a physical environment, observed by a user through a headset, goggles, tablet, or any other screen (phone, computer, television, etc). This technology presents opportunities for efficient training in industrial and academic applications, leading to more streamlined and reliable fabrication and inspection processes [2].

A number of AR tools have been developed in industry for maintenance or composite manufacturing assistance, including Airbus (MiRA) [2], Boeing [3], Anaglyph (PlyMatch) [4, 5], and InFactory Solutions (VisinPro) [4]. For instance, PlyMatch aims to improve the accuracy of the layup process using a camera positioned above the composite part. The feed from the camera is processed by a computer nearby, providing alignment information for the ply being hand-laid. A possible downside for training students in an academic setting using this technology is that assistance is provided on a nearby monitor, meaning the operator needs to look away from the composite while manufacturing. AR-based systems developed for specific training of hand layup manufacturing and bonded assembly repair include LayupRITE [6] and Nezhad et al. [2]. The former utilizes projection-based AR to project assistive markings on the manufacturing workstation. This product uses a Kinekt to recognize user interaction, a projector positioned above the workstation, and a computer to process the system in its entirety. Nezhad et al. [2] developed an AR system for composites bonded assembly and repair with tablet or HoloLens terminals. Functionality was demonstrated in a laboratory setting for an aerospace grade composite repair scenario. Finally, Advanced Composites Training [7] utilizes a HoloLens 2 headset worn by an instructor to demonstrate manufacturing processes through live streaming. Students tune in remotely and view the tutorial through the instructor's perspective with the HoloLens' cameras. In this case, students get no hands-on experience manufacturing composite materials.

This project's main purpose is to develop an AR-based system to enhance composite manufacturing hand layup training in an academic setting, where students can learn through remote or hands-on experiences. This paper presents a first version of an AR-based training system for composite material manufacturing (AR4CMM), integrated with a research lab workstation (shown in Figure 1(a) and (b)). The manufacturing process to demonstrate the application was vacuum bag only (VBO) wet layup. A HoloLens 2 headset was selected to enable hands-free and hands-on implementation with live streaming capabilities. An adaptable lighting system was integrated into the workstation to provide real-world, visual feedback and updates during the manufacturing process. Throughout tutorial development, the AR system was tested for efficacy through performance profilers and user testing.




(a)




(b)

Figure 1. (a) View from the workstation while a user is wearing the HoloLens 2 headset with video streaming on a laptop through the HoloLens app. (b) View from the HoloLens 2 headset with user interface overlaid on the real-world workstation during the first tutorial step (cutting consumables and fabric plies). Yellow, dashed boxes represent augmented reality elements, while blue, solid boxes represent real world elements.

## 2. METHODOLOGY

Figure 2 presents the overall product architecture for all three main sub-systems (SS): SS1) AR lighting, SS2) composite manufacturing tutorial software, and SS3) AR headset. This section summarizes the methodology used for the AR environment and software architecture, hand layup tutorial development, real-world lighting system integration, and 3-stage user testing with novices and experts.

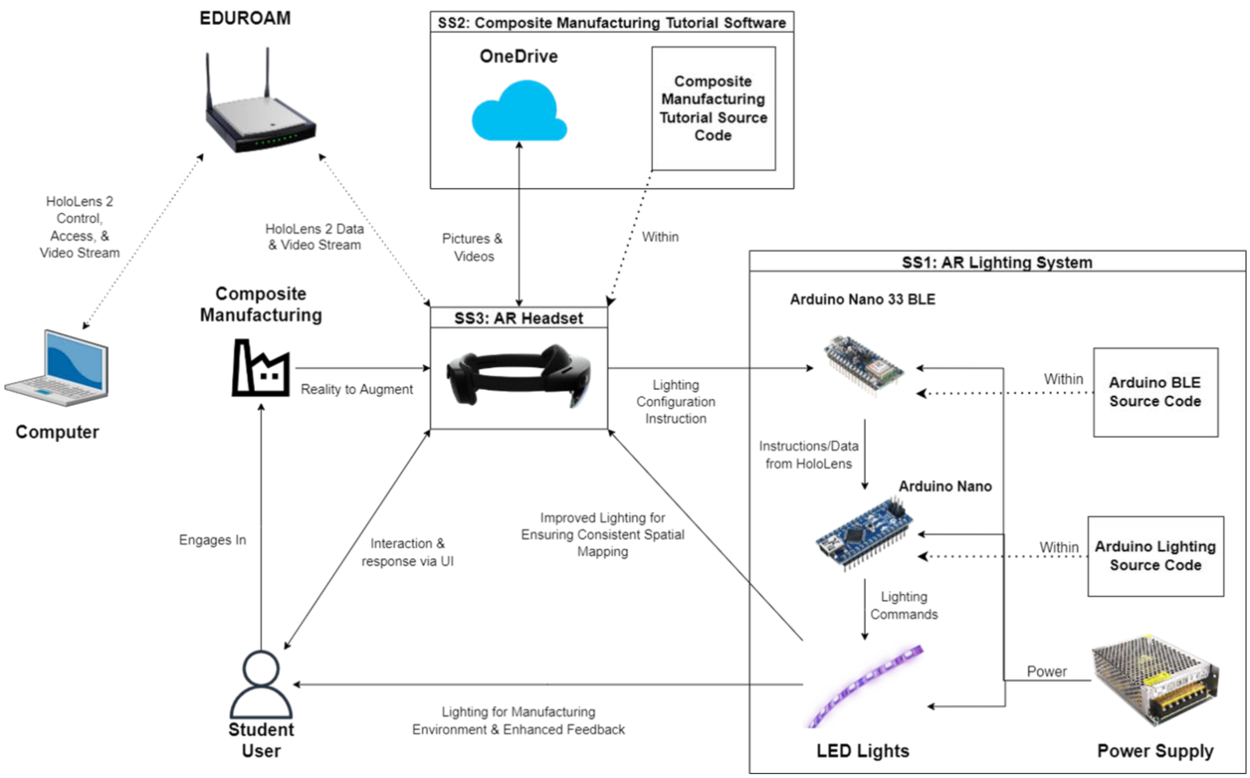



Figure 2. Overall product architecture for all sub-systems (SS1: AR Lighting System, SS2: Composite Manufacturing Tutorial Software, and SS3: AR Headset).

### 2.1 AR environment and software architecture

A HoloLens 2 headset (Microsoft, Redmond, VA, USA) was selected to implement the AR environment. Specifically, the HoloLens 2 allowed for several features, such as speech recognition, spatial mapping, interactive holograms, Bluetooth, machine learning model support, network support, and Cloud support.

Three graphics engines were compared before final selection: JavaScript [8], Unreal [9], and Unity [10]. JavaScript was immediately ruled out, as this engine is newer in terms of HoloLens 2 development, and there can be potential unforeseen restrictions and general support. Additionally, this engine does not support the Mixed Reality Toolkit, which is essential to expediting the development of the application. Likewise, Unreal has recently started being used in conjunction with the HoloLens 2, but is still newer than Unity and lacks much of the support seen with Unity (i.e. various packages, libraries, and community support). Additionally, Unreal is typically used in the VR setting and is intended for video games that are targeting realism. Since the goal for this project is to create a training guide that does not requires extensive graphics like game development, Unity, which is implemented using C#, was chosen as it provides more than enough capability for designing the intended project. Additionally, Unity has been used for AR much longer than the other options, meaning there is a much larger community of developers, documentation, and support available for developing with this engine.

### 2.2 Composite manufacturing tutorial development

The main goal of this tutorial was to teach users to carry out VBO hand layup without external assistance. For the initial version of the tutorial implementation, VBO wet layup was selected as the main manufacturing method as it involves a large number of steps and can later be adapted for hand layup with prepregs. The tutorial was developed based on an existing written procedure and videos available from previous students in the Department of Mechanical Engineering at LSU. For training purposes, the default tutorial was developed for a carbon fiber (CF)/epoxy [0/45/90] flat panel, but a customized layup can be implemented and adapted to a different mold. CF fabric with 2x2 twill 3k weave (Hexcel AS4, Composite Envisions, Wausau, WI, USA) and epoxy system (105-B epoxy resin and 206-B hardener, West System, Bay City, MI, USA) were used during user testing (described in Section 2.4).

Figure 3 shows the overall tutorial architecture implemented on the HoloLens 2 headset. When first beginning the AR tutorial via the headset, the user can choose to start a new manufacturing session or load a previous session (in the event that they stopped midway through a manufacturing session). Following this selection, if the user is new to the system, they will have the option to go through an AR tutorial explaining how to use the headset. This stand-alone tutorial allows the user to experience and test some of the technologies implemented in the composite manufacturing tutorial, such as voice commands, lighting system functionality, and holograms. The user will then have the option to select whether they would like to manufacture a custom composite layup or a default layup (i.e. CF/epoxy [0/45/90] flat panel). The customization option requires the user to fill in various parameters regarding the layup, such as number of plies and orientation. A safety/personal protective equipment (PPE) checkpoint ensures the user is wearing the required safety gear for manufacturing. The actual manufacturing tutorial was divided into four modules: I. Film and fabric cutting (release film, breather cloth, vacuum bagging film, fabric plies); II. Mold preparation (cleaning and release agent application); III. Resin preparation (mixing); and IV. Laminate layup and vacuum bagging. Each module contains instruction steps and checkpoint questions to ensure that users are learning the process as opposed to simply “going through the motions”. Once the user completes the final set of checkpoint questions in module IV, they are prompted with a completion screen detailing how to clean the workspace.

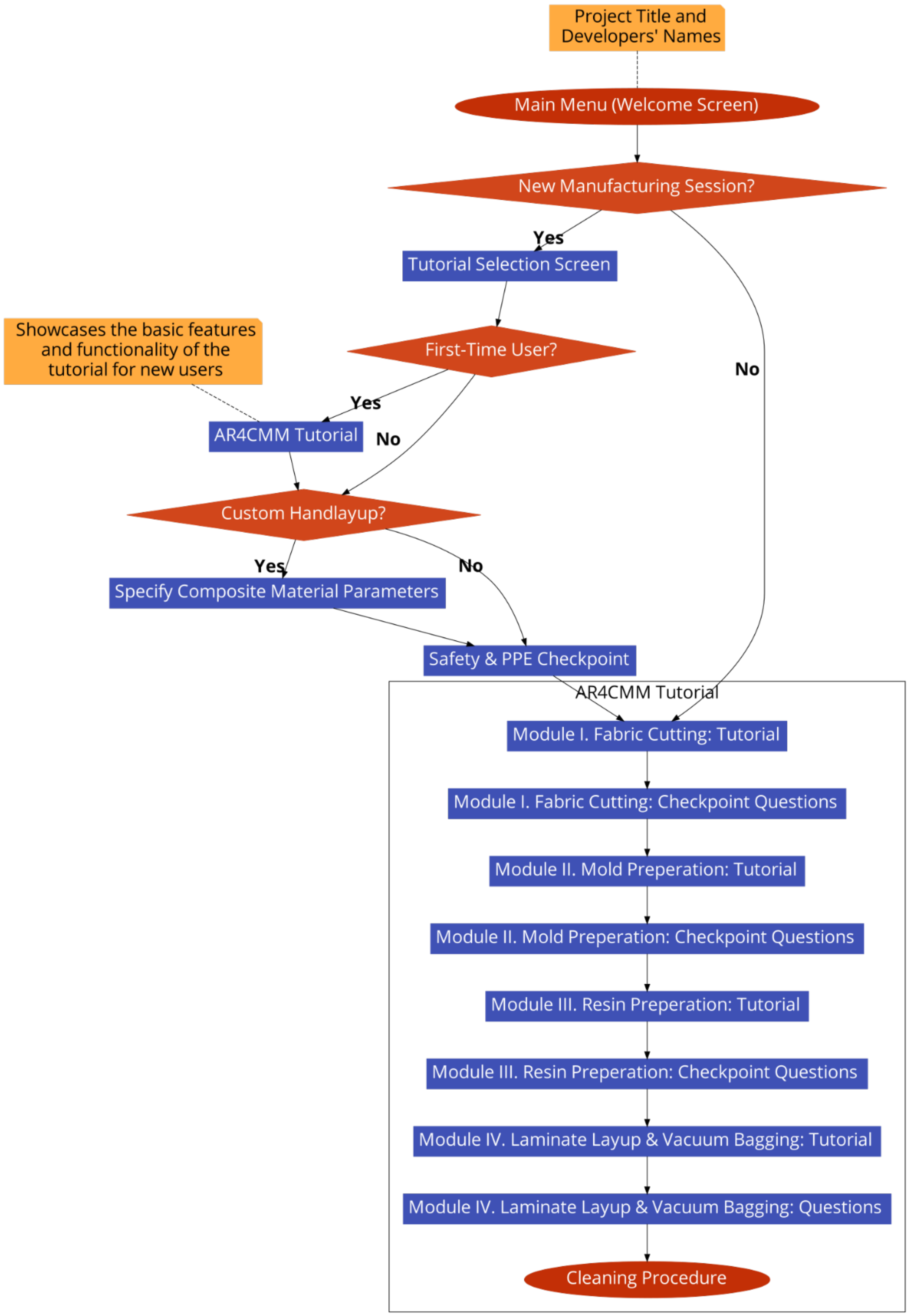



Figure 3. Overall tutorial architecture implemented on HoloLens 2 headset.

### 2.3 Lighting system architecture

A custom-designed LED lighting system was installed on the workstation (Figure 1) for two main purposes: 1) ensure that the manufacturing workstation's illuminance level is adequate, and 2) provide guidance to the user by indicating tool location on the shelves, acting as a timer, and evaluating checkpoint questions answers through color changes. Two light strips (model WS2812B) were installed on the shelves above the work table. Those strips are composed of pixels containing three LEDs (one for each color RGB) and a signal-boosting chip that ensures data is not altered as it passes from pixel to pixel. As seen in Figure 2, an Arduino Nano microcontroller was selected to command the light strips. Communication between Arduino Nano and HoloLens 2 was established with an additional microcontroller, an Arduino Nano 33 BLE, acting as a Bluetooth receiver. This Arduino 33 BLE serves as the receiver of the HoloLens 2 commands. Once this microcontroller receives a command, it transmits it to the regular Arduino Nano, which executes the appropriate lighting command, allowing the intended lighting effect to be displayed on the connected LEDs.

### 2.4 User testing

In addition to informal feedback from students in the composites manufacturing laboratory at LSU, formal user testing was carried out to gather feedback through three phases. This was done as the AR4CMM tutorial was developed to ensure improvements were seamlessly integrated. At this stage, four individuals (two “experts” and two “novices”) have participated in user testing for a total of 12 testing sessions. Experts were defined as individuals possessing prior experience with hand layup composite manufacturing. Novices were defined as individuals possessing no experience or knowledge in composite materials and manufacturing. After each phase, the user was asked to fill out a questionnaire where statements were rated on a scale of 0 to 10. Table 1 summarizes the main topics on which feedback was gathered. The target for success was defined as an average of 7/10 for all users. In addition, answers to checkpoint questions and duration of each step were monitored to assess the users’ understanding throughout the tutorial phases. For this study, the final quality of the laminate was only assessed for number of plies and their orientation. Additional users will be recruited in the next six months to gather more data and sustain continuous improvement.

Table 1. User testing phases and topics included in the post-tutorial questionnaires.

| Phase I: Introduction to AR system | |
|---|---|
| 1. AR headset comfort.<br>2. Clarity of heads-up display.<br>3. Voice controls. | 4. Clarity of each tutorial step.<br>5. Need for external assistance.<br>6. Knowledge gained upon completing the tutorial. |
| **Phase II: Sheet cutting** | |
| 1. AR headset comfort.<br>2. Clarity of heads-up display.<br>3. Voice controls.<br>4. Clarity of steps in the sheet cutting procedure. | 5. Need for external assistance.<br>6. Knowledge gained upon completing the tutorial. |
| **Phase III: Mold preparation, resin preparation, ply stacking, and vacuum bagging** | |
| 1. AR headset comfort.<br>2. Clarity of heads-up display.<br>3. Voice controls.<br>4. Clarity of steps in the mold preparation procedure.<br>5. Clarity of steps in the resin preparation procedure. | 6. Clarity of steps in the wet layup and vacuum bagging procedure.<br>7. Need for external assistance.<br>8. Knowledge gained upon completing the tutorial.<br>9. Confidence that laminate was correctly manufactured. |

# 3. RESULTS

## 3.1 Features implementation and user interface

Functional decomposition of the AR-based training system was first performed to insure all expectations for student training would be met. As such, three main functions were determined as the most important: 1) educate about composite manufacturing, 2) display 3D user interface (UI)/heads-up display (HUD), and 3) facilitate optimal environment for AR. Since the main users for this product are students, it was not desirable for them to simply “go through the motions”, but rather to experience the process and learn in a kinesthetic way. Sub-functions for each main functional requirement are listed in Table 2.

Table 2. Main functional requirements and features of the AR-based training system.

| Educate About Composite Manufacturing | Display 3D UI/HUD | Facilitate Optimal Environment for AR |
|---|---|---|
| • Display step-by-step instructions<br>• Define field-specific terms<br>• Display videos of proper procedure<br>• Test knowledge via checkpoint questions | • Render multiple holograms at once<br>• Display exploded view of the composite layup<br>• Provide functional buttons<br>• Ensure safety precautions are taken | • Reinforce AR functions with a lighting system<br>• Recognize useful tools in the work area<br>• Operate using touch, voice, and eye controls |

To fulfill those requirements, design concepts were evaluated and selected based on five criteria: education effectiveness, user-friendliness, scalability of application for future expansion and development, ease of use during the tutorial, and cost. Figure 4 to Figure 6 show a few of the main features implemented in the AR4CMM tutorial as screen captures from the user's point-of-view:

- Educate user: Detailed instructions, Technical definitions (Figure 1(b) and Figure 4(a)), and Checkpoint questions (Figure 4(b));
- Ensure safety: PPE checkpoints (Figure 4(c)) and Material data sheets (Figure 4(d));
- Display UI: Gaze-activated assistive videos (Figure 5(a)), Assistive images, and Movable holograms for reference with real objects (Figure 5(b));
- Detect interaction: Voice command and Touch controls;
- Reinforce AR functions with lighting system: Brightness settings, Visual results for checkpoint questions, Visual timer (Figure 5(c)), and Tool location indicator (Figure 5(d)).
- Display exploded layup: Expansion and labels for CAD models (Figure 6(a)), and CAD model reference (Figure 6(b)).

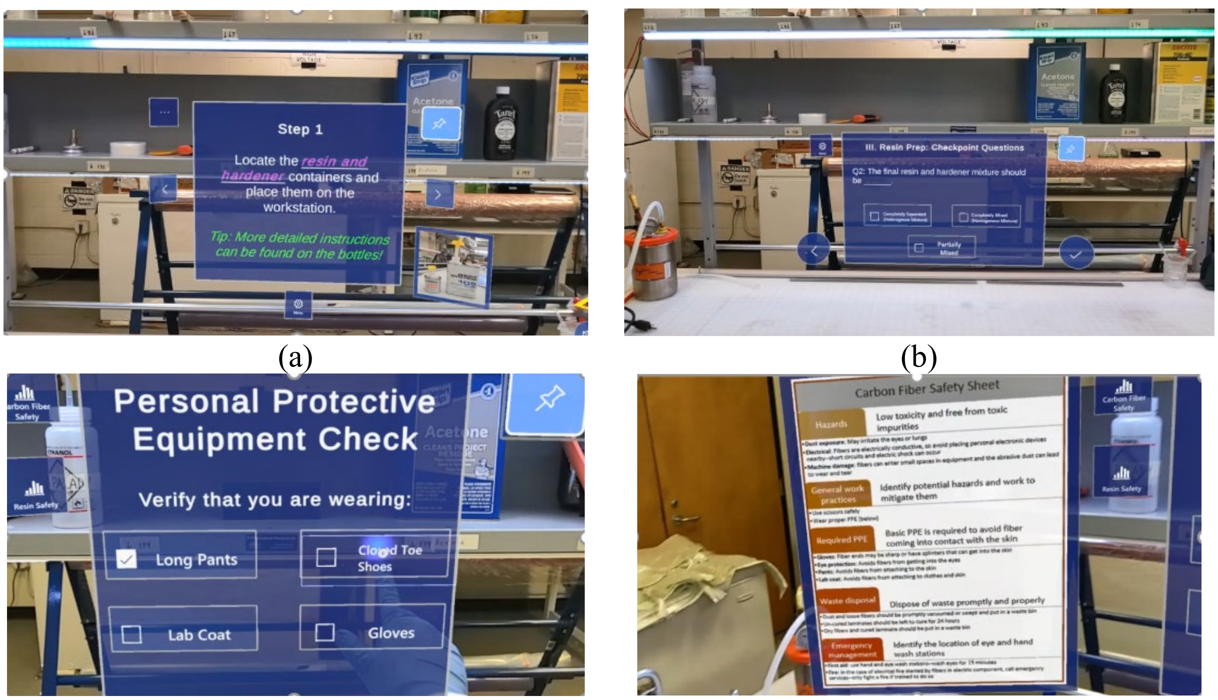



Figure 4. (a) Detailed instructions and technical definitions (touch control or voice command of underlined words); (b) Checkpoint questions included in each tutorial module; (c) PPE checkpoint for each tutorial step, and (d) Safety data sheets.

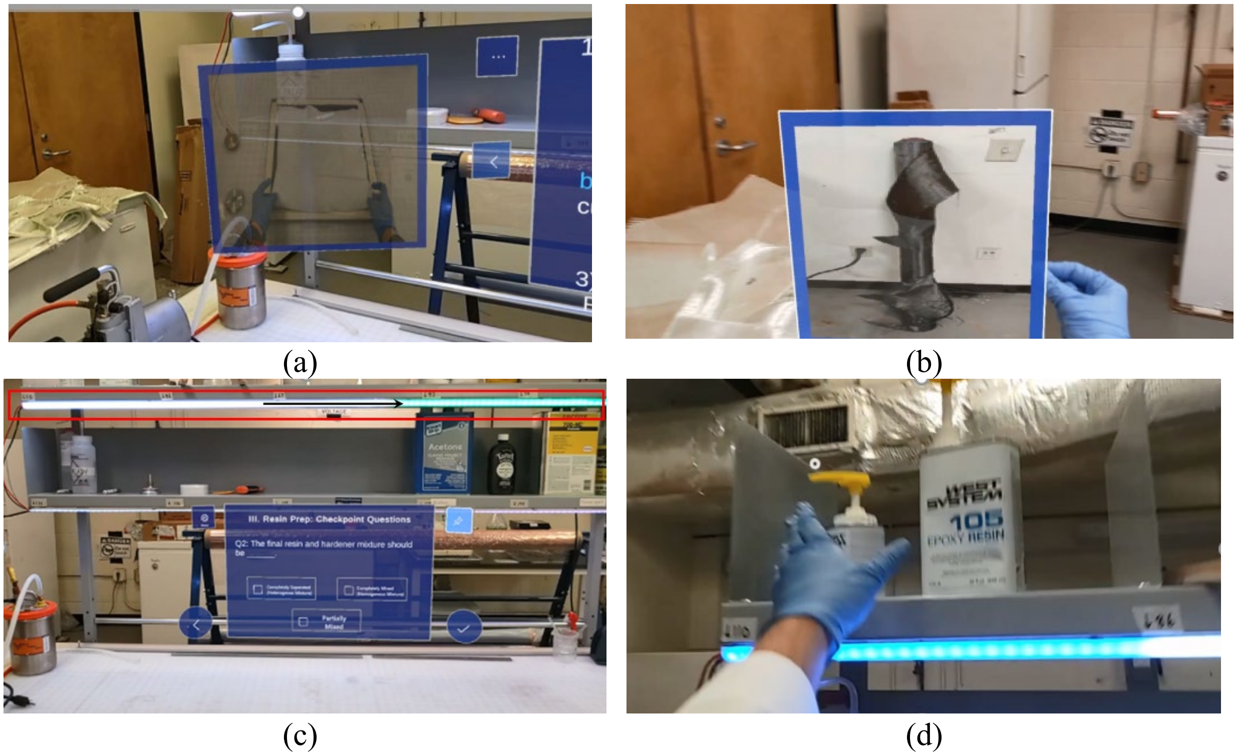



Figure 5. (a) Assistive, gaze-activated videos, (b) Movable holograms/assistive images, (c) Timer implemented through lighting system (gradual color change), and (d) Tool location indicator with lighting system (color change).

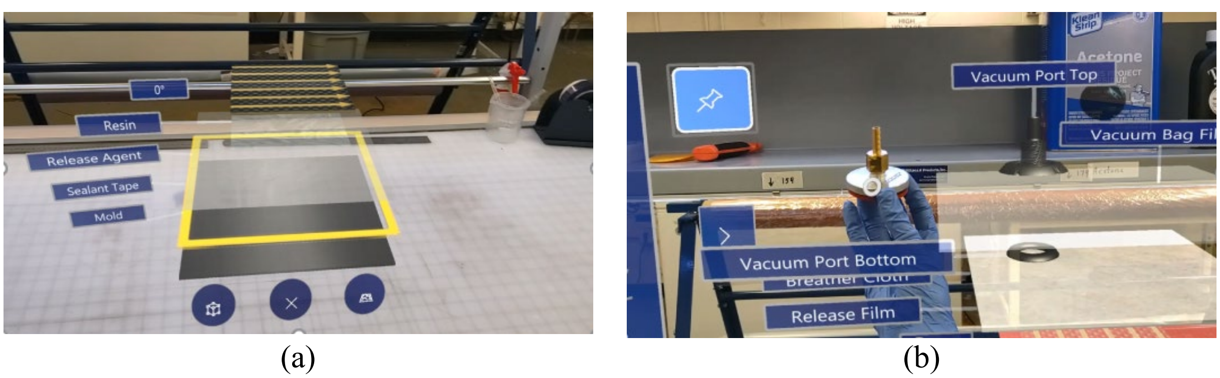



Figure 6. (a) Expandable CAD model hologram of layup with labels and ply orientation, and (b) CAD model reference.

### 3.2 AR system functionality testing

The AR4CMM system functionality was analyzed and tested for software performance, light levels, and auditory threshold. Software performance was tested on the final build of the application during all tutorial steps by analyzing average central processing unit (CPU) utilization (frame per second, FPS), average memory utilization (MB), and peak memory utilization (MB). No crashing, bottlenecking, or functional/logical errors were detected at any point, suggesting a fully stable application.

The light levels were tested with a digital photometer, which reported a baseline measurement at the workstation (without the lighting system) of 380 – 408 Lux. A total of 30 measurements were taken at different locations. With the lighting system on, the light levels increased up to 570 – 610 Lux. While the lighting system effectively increased the brightness at the workstation, it was generally not a concern for the functionality of the AR system.

In laboratory or workshop environments, ambient noise may be a concern for voice commands recognition with the HoloLens 2 system. As the composite manufacturing workstation used for training is located in the vicinity of hydraulic and cooling systems for fatigue testing machines, a decibel meter was used to assess the auditory threshold for the voice commands. Over two weeks, measurements were taken and an average noise level of 69.4 dB (with a peak value of 74.1 dB) was found in the laboratory. At this noise level, the HoloLens 2 experienced no issues in recognizing voice commands. By generating additional noise (white noise, music, etc), it was found that the HoloLens 2 headset had a threshold of 109 dB, after which voice commands were not consistently recognized.

### 3.3 User testing and feedback

User testing was performed in three phases, as detailed in Section 2.4. Figure 7, Figure 8, and Figure 9 summarize the ratings from all four users for the main questionnaire topics. Testers A and D were “experts”, while Testers B and C were “novices” in composites manufacturing. Table 3 shows the average ratings from all users for each testing phase, as well as their average duration. The overall test data suggests that the average target for success of 7/10 was achieved for each testing phase with the AR4CMM system, indicating user satisfaction. However, there is room for improvement for some aspects of the system, such as AR headset comfort and need for external assistance.

After each phase, user feedback was taken into consideration to improve the AR system, when possible. For instance, after Phase I (Introduction to AR system), the heads-up display brightness/transparency was modified for better readability and some of the instruction steps were re-written. Some of the testers also had previous experience with AR and VR systems, which means they did not gain as much new knowledge as other testers. With regards to AR headset comfort, a downward trend in the rating from Phase I to III indicated that longer sessions with the HoloLens 2 were more fatiguing. After Phase II, breaks were included as part of the training procedure for the users to rest, if needed. The voice controls were not implemented until Phase II. During that phase, testers only had access to the “Next” and “Back” commands. By Phase III, the application was expanded in terms of voice commands for each button and special keywords such as “Define” were included for technical terms. This increase in complexity of the feature explains the slight decrease in scoring in this category. Similarly, given that each round consisted of increasingly complex instructions, the slight decrease in instruction clarity was to be expected. Looking at the "assistance needed" question, users only went through an introductory round in which they simply experimented with the AR environment. For Phases II and III, the users actually began manufacturing the laminates and performing tasks, explaining the decrease in scoring between Phase I and II. However, between Phases II and III, there was a decrease in the users' need of assistance during the tutorial. Based on the rating in Phase II, additional assistive features were implemented, such as images, videos, and the "Define" feature.

Given that this project is an education tool, the goal was to ensure each user would gain new knowledge of composite manufacturing. The average ratings from Phase I to III generally increased, indicating an overall improvement in educational effectiveness of the application. This increase is due in part to the inclusion of more features for each succeeding build to better enhance the educational aspect. Checkpoint questions were not implemented until Phase II of testing. Those checkpoints were further improved in Phase III by providing visual feedback and answer keys. Finally, after the last testing phase, testers had to rate their level of confidence that the laminate was correctly manufactured. Overall, the testers felt confident in their ability to manufacture a composite again, except Tester C (Figure 9). It was mentioned that live feedback from the AR technology during manufacturing would improve confidence that the steps are correctly performed by the user. It was visually confirmed that all testers correctly manufactured the laminate (number of plies and orientation) with adequate vacuum bagging and reasonable laminate quality after demolding.

With regards to overall manufacturing duration, many testers actively gave feedback during their manufacturing experience with the AR tutorial, which explains the long durations reported in Table 3. Taking out the aspect of the verbal feedback given by each tester during the process, an average time for actual manufacturing of the composite laminate with the AR tutorial was about 2.5 hours, regardless of the user's previous expertise with composites. In-person training (administered by the laboratory manager or senior graduate students) usually lasts 2 to 2.5 hours, which is comparable to the AR-based system. However, it is to be noted that some aspects of the AR technology (like touch controls, voice commands, and holograms manipulation) can be more time-consuming depending on the user's abilities. Finally, the HoloLens 2 possesses a battery life of around 2.2 hours when running the AR4CMM constantly. Due to the lighting system timer provided for the mold preparation, users can conserve up to 35 minutes of active-use time by allowing the HoloLens 2 to rest during the waiting periods. This fact puts the HoloLens at having a total active use time of about 2 to 2.5 hours, which is adequate to complete the composite manufacturing process.

Table 3. User testing data with average ratings from all testers for each testing phase.

| Questionnaire Topic | Phase I | Phase II | Phase III |
|---|---|---|---|
| AR headset comfort | 8.25 ± 1.71 | 7.00 ± 3.16 | 6.25 ± 3.10 |
| Clarity of heads-up display | 7.50 ± 3.11 | 7.75 ± 2.06 | 7.25 ± 2.22 |
| Voice controls | N/A | 8.75 ± 1.89 | 7.00 ± 1.83 |
| Clarity of each tutorial step | 8.25 ± 1.71 | 7.75 ± 2.08 | 7.50 ± 2.08 |
| Need for external assistance | 8.25 ± 1.26 | 5.00 ± 2.16 | 6.50 ± 2.65 |
| Knowledge gained upon completing the tutorial | 6.25 ± 4.35 | 7.75 ± 3.30 | 9.50 ± 1.00 |
| Confidence laminate was correctly manufactured | N/A | N/A | 9.50 ± 1.00 |
| **Overall Rating Average** | 7.70 ± 1.00 | 7.25 ± 1.00 | 7.43 ± 1.34 |
| **Average Duration (hr)** | 0.8 ± 0.4 | 1.6 ± 0.3 | 2.1 ± 0.3 |

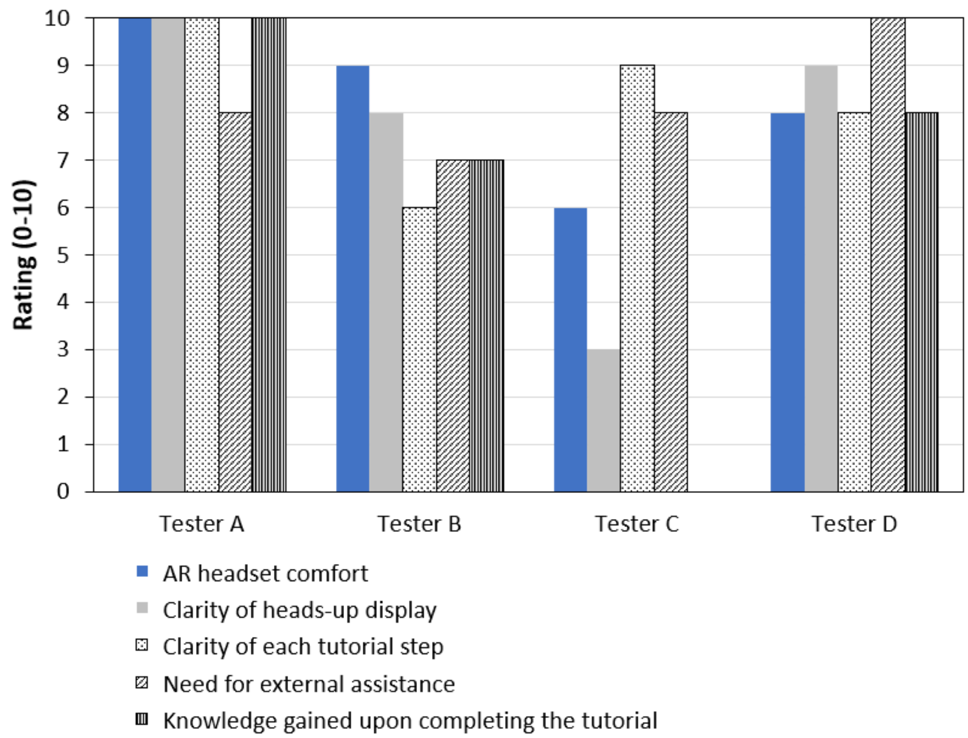



Figure 7. User testing results for Phase I (AR headset tutorial).

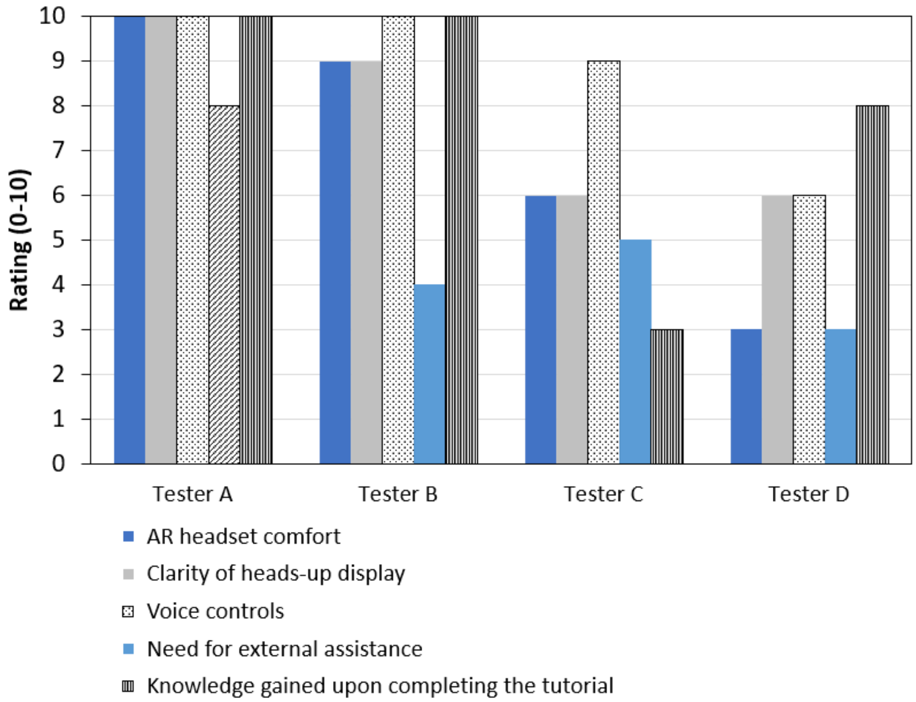



Figure 8. User testing results for Phase II (sheet cutting tutorial).

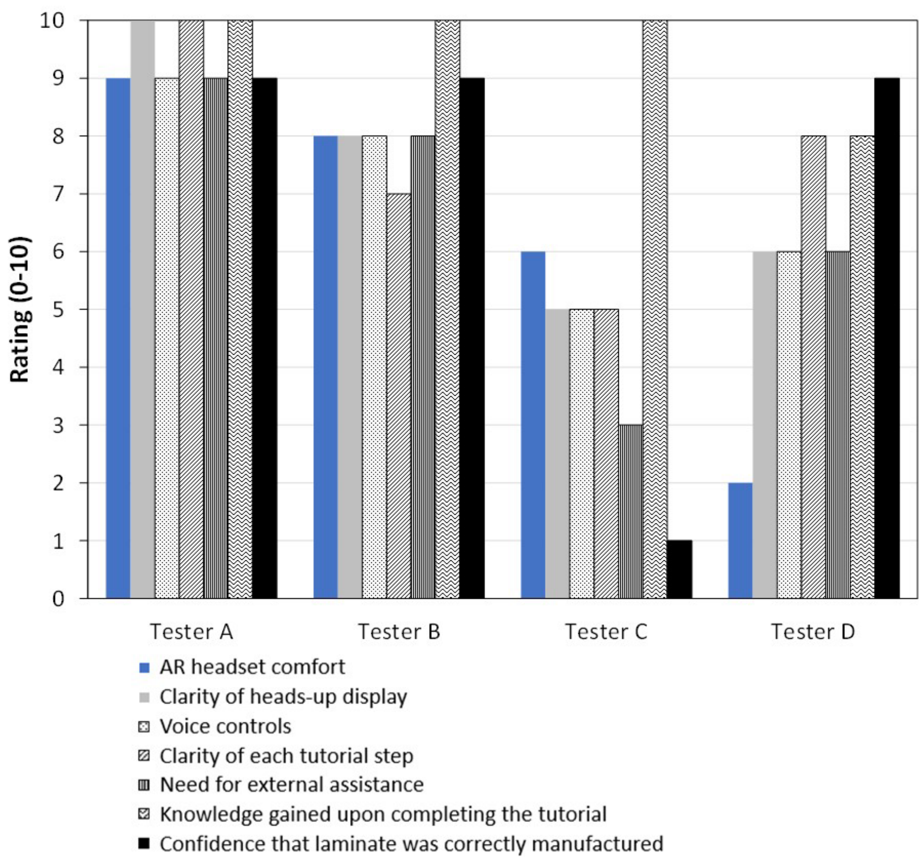



Figure 9. User testing results for Phase III (layup and vacuum bagging tutorial).

# 4. CONCLUSIONS

In this paper, an AR-based system for composite manufacturing (AR4CMM) hand layup training in an academic setting was presented. This first version of the system utilizes a HoloLens 2 headset and is integrated with a research lab workstation. An adaptable lighting system was integrated into the workstation to provide real-world, visual feedback and updates during the manufacturing process. For training purposes, the default tutorial was developed for VBO wet layup of a CF/epoxy [0/45/90] panel, but a customized layup can be implemented and adapted to a different mold. To facilitate educational experience for the users, several features were implemented, such as technical definitions, checkpoint questions, and material data sheets. The user interface and training tutorial were enhanced with gaze-activated assistive videos, movable images and holograms for reference with real objects, voice commands, touch controls, and CAD models reference with expansion and labels. User testing was carried out to assess functionality of the system and gather feedback for future improvement. Average ratings across all users was above 7/10, showing a good level of satisfaction.

Constructive feedback from user testing mentioned headset comfort for extended periods of time and limited interaction/feedback from AR technology. To address those, future directions include implementation of object recognition and machine learning for improved automation with ply positioning on different mold geometries. Further user testing will take place in the next months to gather more data and sustain continuous improvement.

# 5. ACKNOWLEDGMENTS

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