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Augmented Reality-based Operation Training for Coordinate Measuring Machines using a User-Centered Interface Approach

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Abstract. This paper proposes an Augmented Reality (AR)-based CMM training system using a user-centered approach. The primary aim is to deliver real-time training solutions for complex machinery operations, such as CMM tasks, where precision is critical, and users need an interactive and user-friendly learning environment. The training system uses model tracking to superimpose 3D models. A multimodal interface advances the hand-tracking algorithm that displays spherical indicators and real-time feedback onto a physical CMM machine, guiding trainees through complex measurement procedures in a systematic manner. The AR-based training system facilitates key CMM operations, including stylus calibration, the establishment of coordinate systems, and part dimension measurements. It provides real-time visual guidance directly overlaid on the physical machine. Comparative studies show that the accuracy of AR-based measurements is within a range of ±0.05 inch. The AR-based approach enhances user engagement in metrology training applications.

Keywords: Augmented Reality (AR), Coordinate Measuring Machine (CMM), User Centered Interface, Machine Operations.
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1 INTRODUCTION

Industry 4.0 integrates advanced digital technologies such as cyber-physical systems, Internet of Things, and data-driven decision-making for operational efficiency [15]. These technologies facilitate real-time monitoring, predictive maintenance, and autonomous decision-making, thereby promoting intelligent and adaptive production systems. However, the transition from Industry 4.0 to Industry 5.0 emphasizes the synergy between human creativity and machine precision, prioritizing the well-being of workers, sustainability, and ethical considerations in industrial operations. This shift underscores the efficiency but also the quality of collaborations between humans and machines.

Human-machine interactions have become an increasingly critical component in the new industrial landscape to adopt technologies for productivity, worker safety, and overall operational efficiency [1]. Consequently, operators require diverse skills and knowledge that help them minimize errors and mental burdens [18].

Despite these advancements, training methods for machine operations remain largely reliant on dated techniques such as paper-based manuals and instructor-led approaches [11]. These methods often fail to provide hands-on experience, which is time-consuming and poses safety risks. Furthermore, there is a lack of adaptability and interactivity among workers in the complexities of modern technology-driven workplaces, as shown in Figure 1.

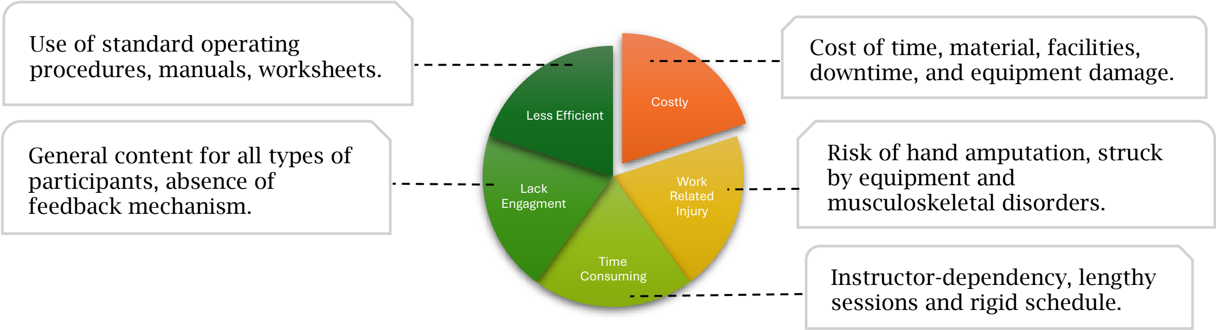


Figure 1: Traditional Training Challenges.

Among various technologies that support user training for machine operations, Augmented Reality (AR) is one of the most promising tools due to its ability to create highly engaging and immersive environments [14]. In contrast to traditional training methods, AR combines theoretical knowledge and practical applications by closely simulating real-world settings for a realistic learning experience. By superimposing digital information onto physical objects, AR enables trainees to visualize complex machine operations, comprehend workflows, and practice tasks in a controlled, realistic environment. AR not only enhances comprehension but also reduces the cognitive load on users, as information is presented in an intuitive and contextually relevant manner [20].

Furthermore, AR offers real-time, step-by-step guidance that adapts to the user's pace and skill level. This reduces the likelihood of human errors in the workplace. The errors are often a consequence of misinterpretation or lack of hands-on experience. Additionally, AR-based training can simulate high-risk scenarios without exposing workers to actual dangers, thereby improving safety and confidence during the learning process. As industries increasingly adopt AR for training, it has the potential to revolutionize workforce development, making it more accessible, efficient, and aligned with the demands of Industry 5.0.

AR has been applied in various fields such as medical, military, construction, aviation, and industrial training, but its use is still limited in certain specialized areas, such as the operation training of the Coordinate Measuring Machine (CMM). The operation of CMM requires precise configuration and calibration to guarantee accurate measurements, which is essential for ensuring the final product meets the required specifications [21]. It involves several steps, such as stylus qualification, establishment of the part coordinate system, features measurement, and analysis of data, as illustrated in Figure 2. The measuring workpiece requires the knowledge to decide the required touch points of the measured part and path planning for the measurement sequence, which relies on the user experience.

Given the critical nature of these applications, correct and efficient operations of CMM are necessary. Challenges such as the development of accurate tracking systems, the creation of user-friendly interfaces, and the need for robust hardware capable of handling the precision required in CMM operations must be addressed. In the context of complex operations, such as CMM workflows, a user-centered interface is essential for enhancing usability and operational efficiency to actively involve users in each phase of the process [13], ensuring that their needs, preferences, and constraints are systematically considered. By prioritizing user requirements, the resulting interface becomes intuitive, accessible, and effective, ultimately improving both user experience and task performance.

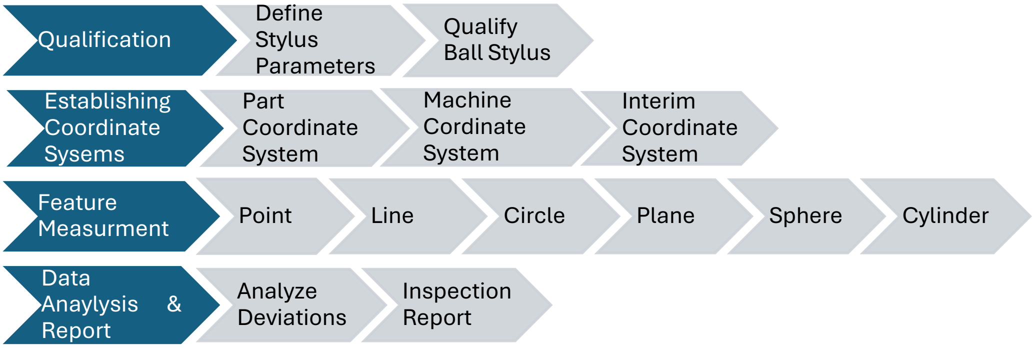


Figure 2: CMM Operations.

This paper proposes an AR-based CMM training system using a user-centered approach. The training system superimposes 3D models, digital instructions, visual cues, and real-time feedback onto the physical CMM machine, guiding trainees through complex measurement procedures in a systematic manner. An intuitive multimodal interface is used to enhance user engagement and facilitate seamless interaction with the training content. This approach not only enhances the learning experience but also mitigates the potential for errors during the training process.

The remaining parts of this paper are organized as follows. Section 2 provides a comprehensive literature review, critically analyzing the existing research on CMM operations, AR training, and user-centered approaches. It also highlights key advancements and identifies gaps in current knowledge. Section 3 introduces the AR-based training system using multimodal AR training techniques to enhance the effectiveness of training programs. Section 4 details the implementation of the proposed system. Section 5 outlines the evaluation methods to assess system performance. Section 6 summarizes the results and proposes directions for future research on AR-based CMM training systems.

2 LITERATURE REVIEW

2.1 Coordinate Measuring Machine (CMM) Training

Training operators to master CMM workflows remains a critical challenge in industries where they demand zero-defect manufacturing production [16]. The CMM operations encompass the probe calibration, coordinate system alignment, and dimensional measurement, which present challenges for novice operators. The machine calibration and environmental conditions play a critical role in the measurement accuracy, thereby further underscoring the critical need for robust and comprehensive training methods.

Traditional methods, such as static manuals or instructor-led demonstrations, provide structured learning environments and expert guidance, but both approaches use a fixed schedule with limited hands-on experience, leading to inefficiencies and measurement errors [8]. Some studies acknowledge that the hands-on instruction can lead to improved performance and high employee retention, but places additional financial strain and fails to address the tactile and procedural nuances of CMM operations [5].

Even emerging training systems, such as VR-based simulators, struggle to replicate the tactile feedback and environmental variability inherent to physical CMM operations. For instance, Khan and Peng[8] developed a VR-based CMM training system to simulate tasks like the stylus qualification and coordinate system selection, significantly reducing costs and risks associated with physical training. However, their fully virtual environment lacks the contextual fidelity, as trainees cannot interact with physical machines or workpieces. Additional advancements were realized with the introduction of AR into CMM training environments. For instance, Wang et al. developed an AR-based Virtual Coordinate Measuring Machine (VCMM) using an image processing approach for mapping joystick movements into a virtual CMM environment [23]. It recognizes different gestures and interprets them into corresponding instructions to control a system. However, this approach retains hardware dependences such as joysticks that increase complexity and fail to address the tactile precision required for micrometer-level CMM workflows.

These limitations underscore the need for solutions that bridge the gap between simulations and real-world CMM operations. Also, it highlights the need for improved gesture recognition systems to eliminate peripheral dependencies while ensuring robust accuracy in dynamic industrial environments.

2.2 Augmented Reality-Based Training

Several research activities have explored the potential of AR across various industries [12]. AR was mostly used in the gaming and entertainment industries, but in recent years, AR technologies have become increasingly popular in professional training and industrial settings.

Unlike VR, AR overlays digital information over the user's real-world view, allowing users to interact with both physical and virtual aspects simultaneously [20]. AR has significantly improved production efficiency by providing real-time guidance, helping workers learn skills quickly, and reducing both training time and material waste [22]. For instance, an AR-assisted guidance system for the assembly of avionics equipment was developed to provide dynamic assembly instructions overlaid onto the real-world environment by real-time pose tracking [25]. This method increased worker performance and reduced errors in assembly tasks. The advantage of AR is further evaluated in material forming and machining processes, where AR training showed faster completion time and fewer errors compared to traditional video or paper-based manuals [22]. AR also offers significant advantages in railway maintenance training and task execution processes by providing realistic and engaging content [16]. Similarly, in the tool change process, AR reduced cognitive load by overlaying visual cues and instructions onto the real-world environment. The step-by-step guidance enables users to perform tasks easily and efficiently, improving overall effectiveness [10]. AR is found to be particularly effective for initial task exposure, as it reduces cognitive load compared to other technologies [2, 26]. This also complements the findings of another author who developed an AR-based tutorial system for fundamental manual metal arc welding training [19].

Initially, AR relied on marker-based systems, where predefined fiducial patterns (e.g., QR codes) anchor virtual contents. While these systems achieve high tracking accuracy, they fail in dynamic settings where placing physical markers on machinery or workpieces is impractical. In contrast, markerless AR combines the flexibility of marker-free interaction with the efficiency of lightweight algorithms. Techniques like Simultaneous Localization and Mapping (SLAM) or feature-based tracking use natural environmental features such as edges of machine or workpiece's geometric contours to anchor virtual content without markers or pre-training. Recently, the use of deep learning techniques has also shown great advantages in markerless AR. Through deep learning, it is possible to obtain more accurate detection. However, deep learning demands extensive datasets and significant computational resources. These requirements pose challenges to achieving real-time performance in environments with limited resources.

Despite these advancements, AR's application to precision measurement tasks, particularly in CMM operations, remains underexplored. Existing studies predominantly focus on assembly or maintenance tasks, neglecting the procedural rigor and micrometer-level accuracy required for CMM operations [10]. This gap highlights an opportunity to leverage AR's contextual fidelity and real-time feedback for CMM training, combining the interactive training with the tactile demands of physical machine operations.

2.3 User-Centered Interface (UCI)

The efficacy of AR systems relies on intuitive user interfaces, particularly in complex operations that process customized products and require distinct measurement setups and parameters. Most AR systems are developed without a strong focus on user-centered interfaces, leading to usability issues. These types of systems increase the cognitive load for end users as they manage various product configurations [3]. Factors such as inputs, structure of the task, process operations and output are the elements that contribute to the overall task complexity [4]. The cognitive load rises with complexity and thus leads to frequent errors, hinders learning, and decreases user satisfaction [3]. Issues like unclear instructions, visual clutter, and poorly positioned virtual elements also negatively impact user experience and training effectiveness [2, 22, 25].

A user-centered approach involves the user in every phase of the process. This is particularly important for the user interface, which is intuitive and easy to use in complex operations [13]. A previous study emphasized that involving end-users in design phases improves usability and reduces cognitive overload. An AR tourism app was developed through a user-centered design approach, resulting in a system that is easy to use and aligned with user needs [24]. Similarly, an AR interface integrates eye-hand menus for unimanual interactions. This design focuses on natural user interactions, demonstrating that incorporating user-centered methods can lead to intuitive and efficient AR interfaces [17]. These studies highlight the critical role of interactions in aligning the user interface with user needs to enhance the effectiveness of immersive training. Recent research indicates that novice users tend to favor the voice input over gestures due to its greater ease of learning and use. However, when engaging in practical applications, users demonstrate a preference for a multimodal approach that combines both voice and hand interactions, suggesting that integrating multiple input methods can enhance usability and learning efficiency [9]. This preference becomes even more evident in complex systems where users are required to manage multiple tasks simultaneously. In such environments, AR-based systems often struggle when limited to hand-based interaction methods, as they can increase cognitive load and reduce task efficiency [5]. As highlighted in Table 1, challenges of using only hand-based interfaces in complex machinery tasks further reinforce the need for multimodal interaction strategies to optimize user performance and improve overall system effectiveness.

Challenges	**Description**	**Impact**
Fatigue Issue	Continuous use of hand interactions for extended periods of time leads to strain and discomfort.	User performance is reduced, and the training effectiveness is impacted.
Cognitive Overload	A lot of instructions require the user to remember the number of gestures to perform the task correctly.	Complex tasks and instructions lead to frustration.
Occlusion	Poor lighting or hand interactions can block the camera view and disturb the gesture detection.	The system fails to detect the gesture when the user's hand is positioned in a way that blocks the camera view.
Precision issue	Hand interaction often faces precision issues due to user instability and system ineffectiveness.	Increased frustration of the user and repeated task adjustments and increased completion time.
Accessibility	Hand-only systems may not be accessible to users with physical disabilities or motor impairments.	Reduced system usability due to the exclusion of certain groups.
Novice user	New users may find hand gestures unintuitive, especially if the system lacks clear guidance or feedback.	Reduced engagement of users in training.

Camera position dependency	Hand interaction is dependent on the camera position and won't work if it does not come in the view of the AR camera.	Missed gesture tracking.

Table 1: Challenges with Limited User Interface.

The literature emphasizes the necessity to develop a user-centered AR training system for CMM operations by incorporating two critical components: real-time guidance to enhance measurement accuracy and multi-modal interaction mechanisms to address interface limitations. Furthermore, to mitigate the deficiencies of existing training, the proposed system must be user-friendly, enabling novice operators to execute complex CMM tasks effectively.

3 PROPOSED AR-BASED TRAINING SYSTEM FOR CMM OPERATIONS

3.1 Software and Hardware Integration

This AR-based CMM training system is developed using the Unity 6 game engine. This engine is selected for its advanced capabilities in creating engaging training applications. The Mixed Reality Toolkit (MRTK) and Vuforia engine are also integrated to enhance system functionality and support the gesture and voice-based interfaces. These technologies facilitate seamless synchronization between virtual and physical machine states, which is essential for delivering a realistic training experience. The Unity engine's cross-platform compatibility further ensures that the training application can be deployed across multiple devices, including head-mounted displays (HMDs) and mobile systems, without compromising simulation accuracy or interactive responsiveness. This adaptability allows the training modules to be effectively utilized in diverse operational environments.

For real-time interaction and user engagement, the training system incorporates the Microsoft HoloLens 2 AR headset, which enables precise hand gesture recognition and voice command processing. Additionally, this device facilitates intuitive user interactions and allows trainees to engage with virtual instructional content and manipulate digital elements in the AR environment.

3.2 User-Centered Interface (UCI) Approach

The AR-based CMM training system is developed using a user-centered interface approach, where the user feedback plays a critical role in refining the interface throughout the design process. Feedback collected from machine operators and trainees is systematically analyzed and incorporated into successive iterations of the system, ensuring that modifications are aligned with user needs and real-world operational requirements. This design approach enables the creation of a training system that is both accessible and effective for users with varying levels of expertise, enhancing usability and comprehension.

The process begins with the creation of precise 3D models using CAD software such as SolidWorks, ensuring that the geometric dimensions accurately replicate the physical structure and functionality of the CMM, as shown in Figure 3.

An iterative development approach is employed to refine the 3D model, ensuring it aligns precisely with the physical machine. The process includes the seamless integration of CAD models into the Unity engine. Each functionality is rigorously tested to maintain accuracy and authenticity, ensuring the training system provides realistic CMM operation experience. Once finalized, the 3D model is imported into Unity, where interactive elements and AR functionalities are integrated to enhance user engagement and learning outcomes.

To ensure precise object detection and alignment within the AR environment, a feature-based tracking model is generated using Vuforia's Model Target Generator (MTG). This target tracking model is then integrated into Unity, where the Vuforia AR engine is configured to recognize the

CMM's distinctive edges and geometric features under real-world conditions. Comparing with deep learning-based object detection techniques, which requires large labeled datasets for training and high computational resources, Vuforia's markerless tracking approach offers faster, more efficient real-time recognition without dependency on extensive dataset training. The ability to detect and align virtual overlays with physical machines in real-time makes markerless AR more effective and practical for industrial applications, where precision and reliability are critical.

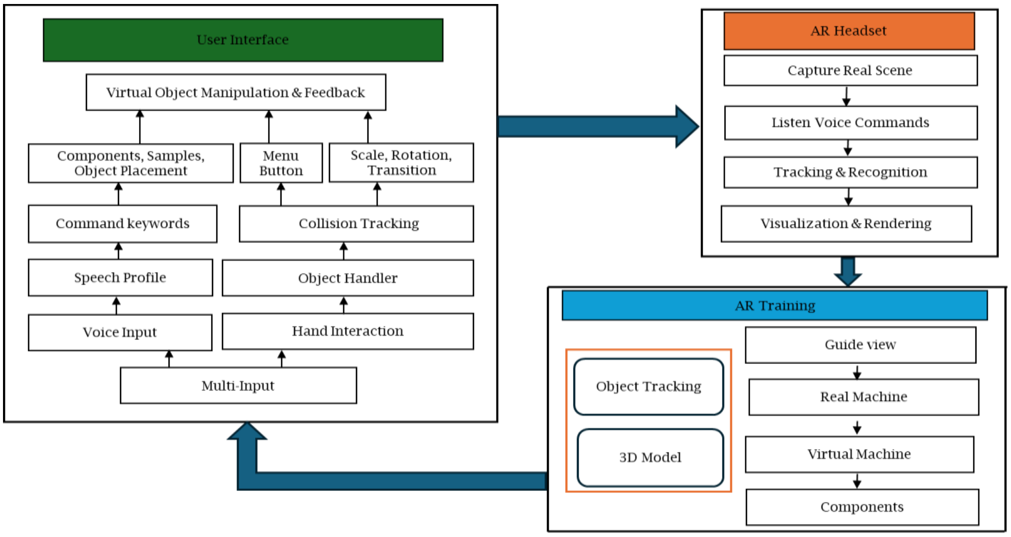


Figure 3: Framework of User-Centered Interface Approach for CMM Operations Training.

The AR-based training system is developed using C# scripting in Unity, enabling simulation of precise machine behaviors such as probe motion, force interactions, and environmental constraints. Advanced physics-based modeling techniques, including rigid body dynamics and inverse kinematics, are integrated to ensure authentic machine operation within the AR environment.

The system also incorporates a hand-based tracking mechanism with collision detection to facilitate natural user interactions and integrates a voice-driven speech command interface, enabling users to perform key CMM operations through natural language input. This approach ensures a responsive, intuitive, and immersive learning environment.

The hand-based user interface is developed using Microsoft's MRTK 2 toolkit. An object manipulator is applied to virtual parts of the CMM using hand gestures. The hand joint tracking mechanism and collision detection are integrated to recognize hand gestures for real-time feedback by instantiating sphere markers on each fingertip, as shown in Table 2. When the distance between the index finger and thumb falls below a defined threshold, the sphere indicators change color to confirm that the virtual object is grasped and can be operated upon. At each frame, the system updates the 3D coordinates of the thumb tip, denoted by O = (O_x, O_y, O_z), along with the four remaining fingertips, F = (F_{ix}, F_{iy}, F_{iz}), enabling the real-time recognition of the user's pinching action. The distance between the tips (pinch gestures) is determined using Equation (3.1).

$$D_{pinch} = |O\text{-}I| = \sqrt{(O_x - F_{ix})^2 + (O_y - F_{iy})^2 + (O_z - F_{iz})^2} \quad (3.1)$$

where the value (I =1, 2, 3, 4) represents the number of tracked fingertips, I=1 corresponds to the index fingertip, I =2 corresponds to the middle fingertip, I=3 corresponds to the ring fingertip, and I= 4 corresponds to the pinky tip. If D_{pinch} falls below a threshold distance T, as shown in Equation

(3.2), the system considers a pinch gesture and triggers visual feedback by switching sphere markers that visually confirm the pinch state at those joints.

$$D_{pinch} < T, \text{ pinch gesture detected} \tag{3.2}$$

By moving fingers apart or bringing them closer together, the object scales up or down when the user places both fingertips near the object and performs a pinch gesture. This directly depends on the ratio of the distance between the new and initial positions of fingers of both hands. The updated size is computed using Equation (3.3),

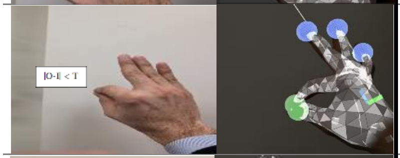
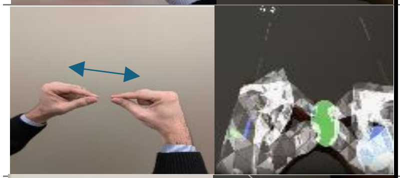
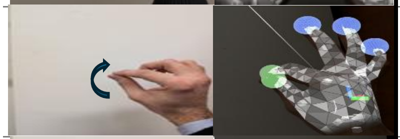
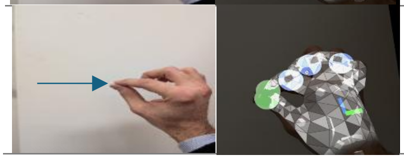
$$S_{updated} = S_{initial} x (\frac{d_{new}}{d_{initial}}) \tag{3.3}$$

where $S_{updated}$ and $S_{initial}$ refer to the updated initial sizes of the object. d_{new} represents the distance between the fingers of two hands, and d_{intial} indicates the distance at which pinch gestures take place.

For rotating a virtual component for CMM setup, a rotation gesture is used. This is calculated by Equation (3.4). Where R_{object} is the updated virtual component rotation, $C_{rotation}$ is the current hand position in 3D space and $R_{initial}$ is the object initial position when pinch gesture starts.

$$R_{obect} = C_{rotation} \, x \, R_{initial} \tag{3.4}$$

Additionally, the integration of transition and air-tapping gestures allows users to accurately position virtual components and initiate actions in training. The AR camera detects these gestures by monitoring hand movements and finger placements.

	Freehand gestures with blue sphere indications, signifies that the user is not interacting with any objects or components.	Freehand gesture.
	Pinch gesture with a green sphere indication ensures secure handling of CMM parts, such as the stylus for visual feedback to validate selections.	Pinch gesture.
	This gesture allows users to scale or zoom in when defining measurement points, particularly where precise probe placement is needed.	Scaling gestures.
	This gesture rotates the stylus and the part during the CMM setup.	Rotation gesture.
	This gesture manipulates the stylus or workpiece.	Transition gesture.

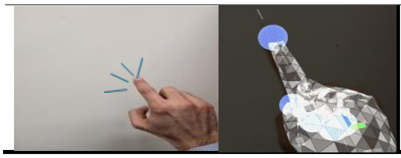
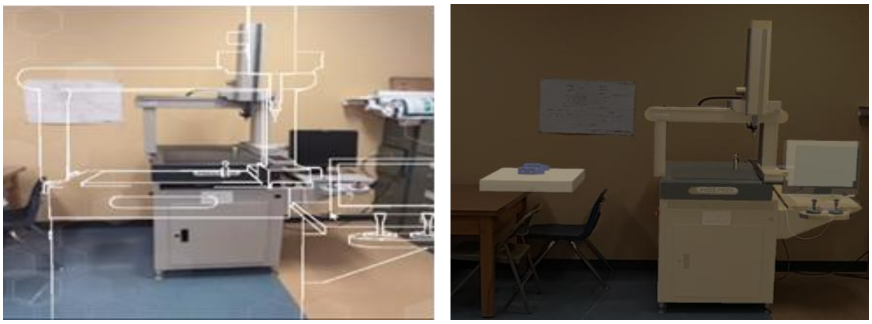
	This gesture interacts with contents to select measurement points on the workpiece.	Tapping gesture.

Table 2: Hand Gestures for CMM Operations.

In addition to hand-based interactions, voice interaction is integrated to further enhance user accessibility and control in CMM operations. This voice interaction is implemented using MRTK 2.0, where predefined keywords are utilized to recognize and process user speech commands. When a command is issued, the AR device's microphone captures the voice input, which is then processed by the speech recognition system to convert it into text. The Natural Language Understanding (NLU) component analyzes the input, extracts relevant keywords, and subsequently triggers the corresponding 3D animations and instructional overlays on the machine components using the toggle function.

4 IMPLEMENTATION OF THE PROPOSED SYSTEM

The system is designed into distinct training phases. Prior to the commencement of the training, a guide view is displayed to align the AR camera with the actual CMM as shown in Figure 4(a). After the object is tracked successfully, the 3D CMM model is rendered and overlaid onto the actual machine, as depicted in Figure 4(b). Using the model target and Vuforia engine, the AR system tracks the geometry of the actual CMM and accurately overlays the virtual CMM.



(a) (b)

Figure 4: AR-Based System: (a) Alignment of Guide View, (b) 3D Model Overlaid on CMM.

The training phases for CMM operations, illustrated in Figure 5, are integrated into the system. When the virtual object is superimposed onto the actual CMM, the user sees menu buttons as shown in Figure 6, offering various options, including Machine Introduction, Stylus Management, Feature Measurement, Coordinate Selection, and Data Analysis.

4.1 CMM Introduction

The training system uses interactive menu-based buttons to guide users through various machine components and functionalities. These buttons are developed using the Mixed Reality Toolkit (MRTK). When the user presses or clicks a button, the corresponding component on the virtual CMM model is activated, with contextual arrows appearing to direct attention to the selected component, as shown in Figure 7. These arrows are dynamically anchored to the machine, pointing toward the relevant component. Furthermore, they adjust their position and orientation in real time as the trainee moves, ensuring continuous and accurate guidance toward the target part.

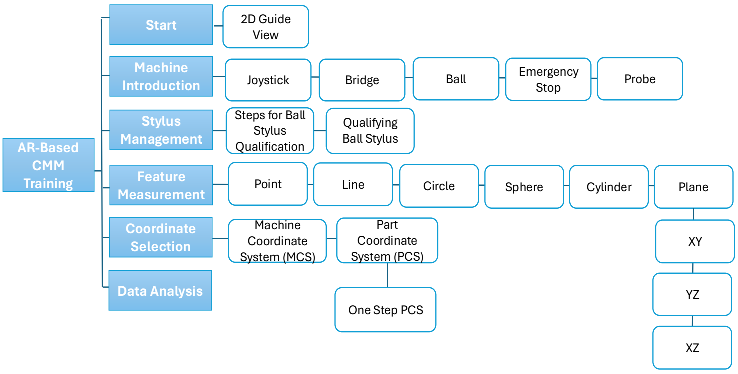


Figure 5: Training Modules for CMM Operation.

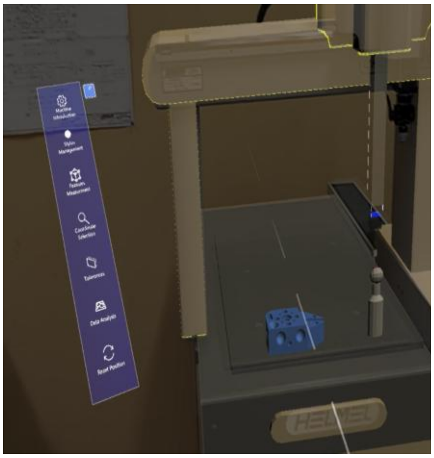


Figure 6: User Interface for CMM Training.

(a) (b) (c) (d)

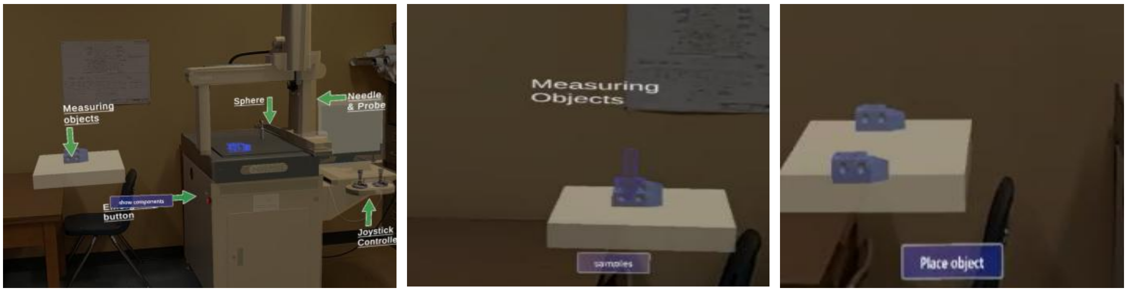
Figure 7: CMM's Component Introduction: (a) Menu-buttons, (b) Emergency Switch, (c) Joystick Controller of CMM, and (d) Measuring Object and Sphere.

The system integrates voice command interactions, enabling users to issue verbal instructions to the system. When a speech command, such as "Show components", is issued during the training session, all machine components are triggered, with each component being identified by its specific name, as shown in Figure 8(a). Another command prompts the AR headset to highlight available objects, assisting the user in selecting a component for measurement, as illustrated in Figure 8(b). Additionally, when the speech command "Place object" is used, real-time feedback is provided by positioning the virtual object onto the machine, as depicted in Figure 8(c).

This hybrid method of presentation ensures that trainees are prepared with the necessary background knowledge to effectively navigate the complexities and nuances involved in CMM training.

4.2 Stylus Calibration

Calibrating a CMM stylus is to ensure accurate dimensional measurements. This process involves touching the stylus tip to a reference sphere multiple times so the machine can determine the stylus's diameter. In this training, a novel hybrid interaction approach is employed that integrates Unity's physics engine with advanced hand-tracking technology to simulate the stylus calibration in a realistic manner. The physics engine manages collision detection, ensuring that when the trainee moves the stylus against the reference sphere, it accurately mirrors the behavior of a physical probe and provides an audible beep. Similarly, advanced hand-tracking delivers immediate visual feedback on fingers whenever users perform pinch gestures to confirm successful grasping of the stylus.



(a) (b) (c)

Figure 8: Operations using Voice Commands: (a) CMM Components Identification, (b) Object Selection for Measurement, and (c) Object Placement Command.

In the stylus qualification process, the trainee first receives real-time visual guidance on how to qualify the stylus, as shown in Figure 9(a). After that, the training session begins with a message indicating "5 touches required" to qualify the stylus. After each successful contact, the message updates to indicate the number of remaining touches as shown in Figure 9(b). Upon successful completion of the calibration procedure, the measured diameter of the stylus is displayed to the user as depicted in Figure 9(c).

(a) (b) (c)

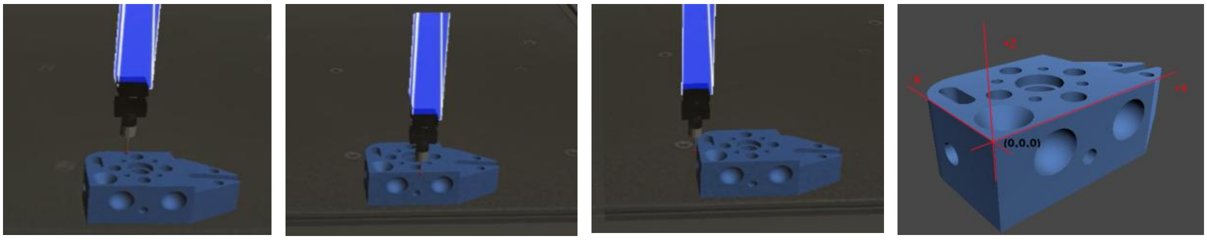
Figure 9: Stylus Calibration: (a) Instruction to Qualify the Stylus, (b) Stylus Qualification Progress with Touch Count Indicator, (c) Confirmation of Selected Stylus Diameter.

4.3 Coordinate Selection

In the training, users are introduced to the selection of coordinate systems for measurement and reporting tasks in the Part Coordinate System (PCS) and the Machine Coordinate System (MCS).

The MCS is a fixed, machine-based reference frame for initial positioning of measurements. This simplified process enables novices to quickly grasp foundational concepts without unnecessary complexity. On the other hand, the establishment of the PCS requires a more detailed interaction procedure based on the geometry of the physical workpiece, and its origin can be located at any selected reference point on the component.

In training, the system instructs trainees to establish the PCS by showing the procedure to tap the stylus against identified datum targets, as shown in Figure 10. The one-step PCS method is integrated in this training; the trainee is guided to touch the stylus tip three times on the top plane (Z-axis), twice on the front plane(Y-axis), and once on the left plane (X-axis) to define a PCS.



(a) (b) (c) (c)

Figure 10: PCS Coordinate Selection Process: (a) Top Plane (Z-axis), (b) Front Plane (Y-axis), (c) Left Plane (-X-axis), and (d) PCS Origin Formed.

The training system employs Unity's physics engine and real-time object tracking to precisely record these coordinate points. When the trainee performs each tap, the system provides immediate numerical feedback, displaying the exact recorded coordinates. Using these data, the system mathematically determines the PCS origin. When four contact points (P1, P2, P3, and P4) are recorded on the top plane, the normal vector and plane equation are computed. Subsequently, data collected from two taps on the front plane, combined with one previously recorded top-plane point, allows the determination of another vertical plane. The intersection point of these computed planes mathematically defines a precise location, the PCS origin (0,0,0), corresponding to a physical corner of the measured workpiece.

4.4 Feature Measurement

Following the coordinate system selection, the next step performs measurements on various geometric features of a workpiece. In the AR training environment, trainees are guided through the selection of different measurement types, including point, line, circle, cylinder, cone, plane, sphere, and cone. The AR system presents MRTK menu buttons, allowing users to choose the feature type for measurement. Upon selection, AR visual overlays and prompts guide the trainee in performing the necessary probe interactions on the real or virtual workpiece. For each feature, trainees engage in a series of stylus-based measurements, where the system records x, y, and z coordinate values upon the probe contact. These recorded points are subsequently processed to decide the required dimensions.

4.4.1 Plane Measurement

Plane measurement determines the geometric characteristics of a plane's surface in 3D space. A plane has attitude, direction, and location. These parameters (attitude, direction, and location) are used to fully describe the plane's position and orientation in 3D space. The system uses the equation of the plane based on the three points collected in the measurement. Using the equation of a plane, given three non-collinear points P1, P2, and P3, the system derives the normal vector n and the position vector $v0$ of the plane. The mathematical representation of the plane is as follows:

$$n \cdot (v - v0) = 0 \tag{4.1}$$

where n is the normal vector to the plane, derived from the cross product of two vectors defined by the 3 points measured. v represents a point on the plane, and $v0$ is the position vector of an arbitrary point on the plane.

4.4.2 Point Measurement

Point measurement in CMM is used to determine the coordinates of a single point. After setting the PCS, the measurement is performed by tapping the workpiece once. The system then records the spatial coordinates of the point. Mathematically, the measured point is stored as a position vector:

$$P = (x, y, z) \quad (4.2)$$

where x, y, and z represent the Cartesian coordinates of the tapped location.

4.4.3 Line Measurement

The line measurement is done by tapping the workpiece on two separate locations to measure their x, y, and z coordinates and compute the corresponding line segment. Once two points, P1(x_1, y_1, z_1) and P2(x_2, y_2, z_2) are determined, the system calculates the distance between them as follows:

$$d = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2} \quad (4.3)$$

4.4.4 Circle Measurement

The circle measurement decides the center location and radius of the holes of the workpiece. The measurement collects the coordinates of points P1, P2, P3, and P4 on the circle. The system then determines the circle radius r as follows:

$$r = \sqrt{(x - x_c)^2 + (y - y_c)^2 + (z - z_c)^2} \quad (4.4)$$

where (x_c, y_c, z_c) represent the circle's center coordinates. These will be determined by applying the least-squares fitting algorithm to the collected points using the error function provided in Equation 4.5:

$$E\,(x_c, y_c, z_c\,, r) = \sum_{i=1}^{N}\left[\sqrt{(x_i - x_c)^2 + (y_i - y_c)^2 + (z_i - z_c)^2} - r^2\right] \quad (4.5)$$

where, E represents the error function, which is used to find the optimal values for (x_c, y_c, z_c,,r) and N is the number of measurement points P. This method minimizes the sum of the squared differences between the measured points and the ideal circle, ensuring the most accurate circle fit.

4.4.5 Cylinder Measurement

The cylinder feature identifies the diameter and attitude of the axis of a cylindrical shape. The attitude of a cylinder's axis is defined similarly to the normal vector of a plane, using the characteristics identifiers AX/Y, AY/Z, AZ/X. The system will collect the 3 points at or near the bottom and 3 points at or near the top of the bore or boss, approximately perpendicular to its axis. The diameter of the cylinder is determined by computing the radius by using Equation (4.6):

$$r = \sqrt{(x_i - x_c)^2 + (y_i - y_c)^2} \quad (4.6)$$

where (x_c, y_c, z_c) represents the circle's center coordinates. These will be determined by applying the least-squares fitting algorithm to the collected points to get the center coordinates using Equation (4.5).

4.4.6 Sphere Measurement

The sphere feature is used to measure the diameter and location of the sphere center. To measure a sphere, five data points around the sphere's surface are collected to determine its center and radius/ diameter. The equation of the sphere radius is decided by:

$$r = \sqrt{(x - x_c)^2 + (y - y_c)^2 + (z - z_c)^2} \quad (4.7)$$

where r represents the distance from the center of the sphere to the collected points on the surface of the sphere. The (x_c, y_c, z_c) will be determined by applying the least-squares fitting algorithm using Equation 4.5.

4.4.7 Cone Measurement

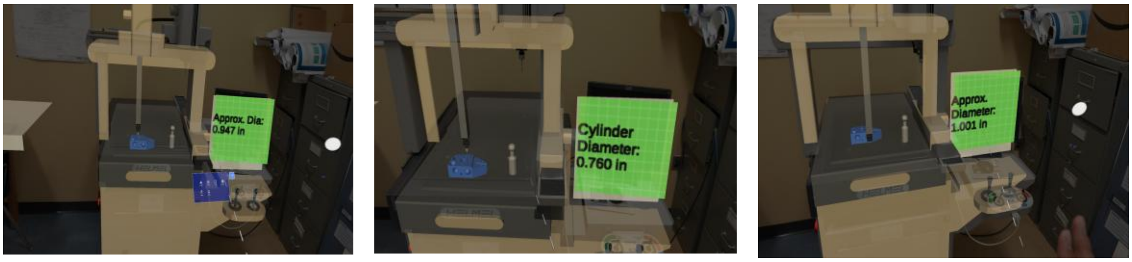
Cone Measurement determines the angle, pierce point, and attitude of the axis and diameter of the cone. The attitude of the cone axis resembles the axis of the cylinder in the projection characteristic. For establishing the slant height and base radius of a cone, points on the base circle and the cone side are measured. For example, 3 data points at the bottom of the cone and 3 at the top of the cone are collected. The base radius is calculated in a manner similar to the measurement of a circle's radius. The slant height is determined by using the Pythagorean theorem:

$$\text{Slant height}=\sqrt{h^2+r_{base}^2} \tag{4.8}$$

where h is the distance between the apex and the center of the base circle, and r_{base} is the base circle radius.

5 SYSTEM EVALUATION

To evaluate the measurement capability of the proposed training system, the measurement of three geometric features, including circle, sphere, and cylinder, is conducted as illustrated in Figure 11. A virtual stylus is used in the AR environment to simulate standard probing procedures. Four points are touched along the inner edge of the circle to estimate its diameter, six points are selected on the surface of the cylinder to compute its diameter, and five points are touched on the surface of the sphere to estimate its diameter.



(a) (b) (c)

Figure 11: AR-based Feature Measurement: (a) Circle Diameter Measurement, (b) Cylinder Diameter Measurement, (c) Sphere Diameter Measurement.

These AR-based measurements are then compared against the physical dimensions of the same features obtained using a CMM machine. The results are summarized in Table 3. The AR-based measurements closely approximate the CMM values with deviations ranging from 0.008 to 0.044 inches. These results suggest that the proposed AR system has sufficient accuracy to support dimensional inspection training and simulation.

Feature	Actual Diameter(in)	CMM Measured Diameter(in)	AR-Based Measured Diameter(in)
Circle	1.000	0.991	0.947
Cylinder	0.750	0.751	0.760
Sphere	1.000	0.993	1.001

Table 3: Comparison of AR-Based and CMM Measurements for Geometric Features.

6 CONCLUSION AND FUTURE WORK

The AR-based training system for CMM operations provides advancement in the domain of precision measurement training. The proposed user-centered approach aligns the training system with the human-centric principles of Industry 5.0. The system incorporates markerless object tracking, multi-input interface, and novel hand-tracking mechanism. It also supports important tasks like stylus qualification, feature measurement, and part-coordinate selection using visual and sound cues. These features allow trainees to interact with the CMM in a risk-free environment, improving both accuracy and efficiency in performing operations.

Therefore, the proposed AR-based CMM training system improves the user experience, usability, and trainee engagement as depicted in Table 4.

Factors	**Traditional CMM Training**	**AR-Based CMM Training (Proposed System)**
Associated Risk	Traditional training method presents a risk of probe damage and safety hazard resulting from unintended collisions or operator errors.	The proposed training provides risk-free environment, preventing any physical damage through virtual probes and collision detection.
Training Efficiency	Longer training time due to reliance on instructors and manual processes.	Reduced training time due to interactive and step-by-step guidance for task execution.
Feedback Mechanism	Users must check the monitor display each time for feedback or corrections during operations.	It provides real-time feedback directly in the user's view, minimizing disruption.
Task Support	Minimal guided assistance for complex tasks such as stylus qualification and part-coordinate selection.	It provides step-by-step guidance with visual overlays and auditory cues, simplifying complex workflows.
User Experience	Limited interaction and relies on static demonstrations and physical controllers/joysticks.	It provides high engagement with multimodal interface, creating immersive experience.
Cost of Training	Traditional training has higher costs due to machine wear and the expenses associated with the instructor's time spent delivering the training.	It has lower costs due to minimum reliance on the instructor.
Alignment with Industry 5.0	It relies on traditional methods without significant technological innovation.	Aligns with Industry 5.0 by incorporating multi-input interfaces and advanced hand-tracking, supporting user-centric approach.

Table 4: Comparison of Traditional CMM Training and AR-Based CMM Training.

6.1 User Evaluation

A user study is proposed to evaluate the effectiveness and perceived workload of the proposed system. The study aims to assess how well the system supports understanding of the CMM operation. In the evaluation, each participant will apply the training system and complete a range of established metric as defined in the task criteria to assess the usability of the system and the cognitive workload they experience. These measures will provide quantitative measures and user experience. Upon the completion of the training, additional questions will be administered to gather feedback of users' overall experience and adaptability.

6.2 Task Criteria

Participants of different user groups will be recruited for this study to complete measurement tasks using the developed training system. The task involves understanding the CMM operation, probe calibration and measuring workpieces.

To evaluate the system's usability and workload, two well-established assessment measures will be utilized: System Usability Scale (SUS) and NASA Task Load Index (NASA-TLX) [2, 14]. The SUS consists of 10 questions that yield a score ranging from 0 to 100, providing an overall usability score. Each question measures a different aspect of usability, such as ease of use, confidence in using the system, complexity and consistency. Participants will rate each questionnaire on a 5-point Likert scale (ranging from 1 = Strongly Disagree to 5 = Strongly Agree). On the other hand, the NASA-TLX consists of six dimensions (mental demand, physical demand, temporal demand, performance, effort, and frustration) with a weighted scoring system to assess perceived workload during the task of CMM operations.

Equation (6.1) gives a range of scores from 0 to 100,where higher scores indicate better usability of AR based training.

$$SUS\ Score = \left(\sum transformed\ scores\right) \times 2.5 \tag{6.1}$$

Equation (6.2) measures the perceived workload for each of six dimensions, with lower scores indicating reduced workload and higher scores indicating increased workload.

$$NASA - TLX\ Score = \left(\frac{\sum(Rating\ of\ all\ dimensions}{6}\right) \tag{6.2}$$

For further analysis, we will compare the usability and workload across different user groups to evaluate the system adaptability in learning and using. Additionally, following questions will be asked after the test to gather further insights:

1) How easy was it in using hand tracking and voice command for CMM Operations?
2) How did the AR interface guide your operations of CMM Components?
3) What is your experience in using AR HoloLens for the CMM measurement task?
4) In what way do you prefer to receive and use the instructions?

The responses from the participants will provide valuable insights, highlighting areas where the proposed system needs improvement for an effective CMM operations training system.

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