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

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Introduction:
Industry 4.0 integrates advanced digital technologies such as cyber-physical systems, Internet of Things, and data-driven decision-making for operational efficiency [4]. Industry 5.0 highlights human-machine interactions and places the well-being of workers at the center of the operations. Traditional training of machine operations relies on paper-based and trial-and-error techniques [6], which lack hands-on experience and are often challenging and inaccessible due to safety hazards.

Among different technologies that support the user training of machine operations, Augmented Reality (AR) is one of the most promising technologies as an effective tool with a highly engaging and immersive environment. AR can closely mimic real-world settings for an interactive learning experience [3]. It can reduce the mental loads of workers, dependency on paper-based training instruction [1], and human errors in the workplace. Although AR has been applied in various fields such as medical, military, construction, aviation, and industrial training, its use is still limited, such as in the operation training of Coordinate Measuring Machine (CMM). CMM is used to measure the physical geometrical characteristics of parts with a high level of accuracy [5]. CMM users must be instructed on correct and efficient operations. This underscores the need to apply new approaches to enhance usability and human cognitive capabilities in CMM operations training.

User-centered approach involves the user in every phase of the process [2]. This is particularly important for the user interface that is intuitive and easy to use in complex operations. This research proposes an AR-based CMM training system based on the user-centered approach to ensure that the training is efficient and easy in operations to meet the training need.

Main Idea:

CMM operations

The operation of a CMM requires precise configuration and calibration for the measurement, which involves processes such as the stylus qualification, establishment of the part coordinate system, and features measurement as illustrated in Fig. 1. Measurement requires the knowledge to collect required touch points of measured part geometric features and plan paths for the measurement sequence, which relies on the user experience.

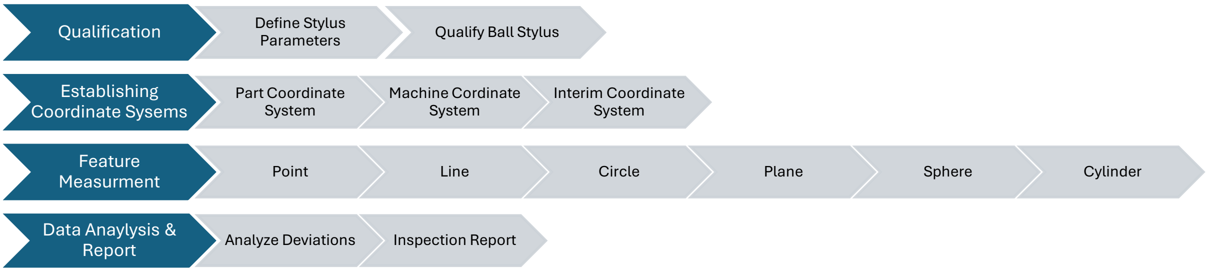


Fig. 1: CMM operations workflow.

User-Centered Interface

A user-centered interface provides step-by-step guidance for CMM operations based on AR to ensure that training is accessible and usable for a wide range of individuals. The interface supports natural user interactions by incorporating voice commands and hand gestures. The framework of the proposed interface is shown in Fig. 2.

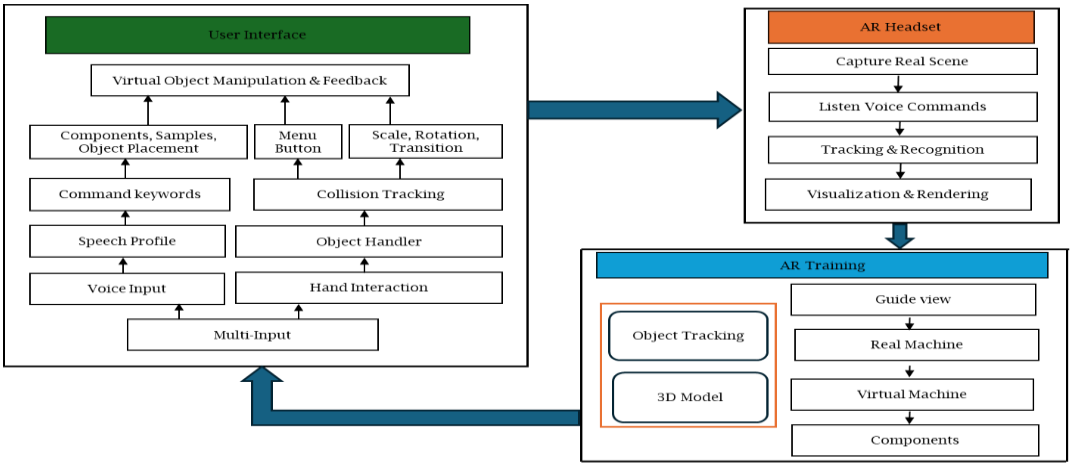


Fig. 2: Framework of user-centered interface for CMM operations training.

CMM Modeling

3D CMM models are built based on CMM operations. Unity and Vuforia software tools are applied to track data produced by the Model Target Generator and replace the Unity default camera with the "Vuforia AR Camera" for AR applications to recognize the actual CMM machine and align with the virtual CMM machine. The training program is developed using the C# programming language in the Unity software to control the AR device. At the start of training, a 2D guide view is displayed to align the AR Camera with the actual CMM. After the object is tracked successfully, the 3D CMM model is rendered and overlaid onto the actual machine.

AR Device

HoloLens 2 AR headset is used to track and recognize hand gestures and voice commands, and display virtual items in the training. The headset supports hand interaction gestures and voice commands of users.

Hand Gestures

The hand interaction in the user interface is developed using Microsoft's MRTK 2 toolkits. 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 Tab.1. 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. 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}). The distance between tips (pinch gesture) is decided by Eqn. (2.1).

$$D_{pinch} = |O\text{-}I| = \sqrt{(O_x - F_{ix})^2 + (O_y - F_{iy})^2 + (O_z - F_{iz})^2} \quad (2.1)$$

where the value (I =1, 2, 3, 4) illustrates 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 Eqn. (2.2), the system considers a pinch gesture and triggers visual feedback by switching the sphere markers that visually confirm the pinch state at those joints.

$$D_{pinch} < T, \text{ pinch gesture detected} \quad (2.2)$$

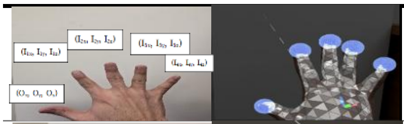
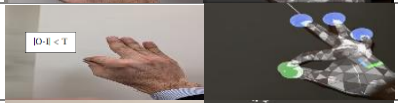
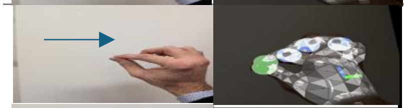
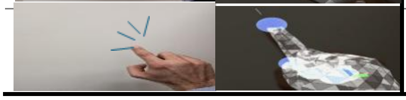
By moving fingers apart or bringing them closer together, the object scales up or down, when the user places both fingertips near the object and performs the pinch gesture. This directly depends on the ratio of the distance between new and initial positions of fingers of two hands. The updated size is decided by Eqn. (2.3).

$$S_{updated} = S_{initial} x (\frac{d_{new}}{d_{initial}}) \quad (2.3)$$

where $S_{updated}$ and $S_{initial}$ refer to the updated initial sizes of the object. Meanwhile, D_{new} represents the distance between the fingers of two hands, while 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 can be calculated by Eqn. (2.4), where R_{object} is the updated virtual component rotation, $C_{rotation}$ is the current hand position in 3D space and $O_{initial}$ is the object initial position when pinch gesture starts.

$$R_{obect} = C_{rotation} \, x \, R_{initial} \quad (2.4)$$

	Blue sphere indications signifies that the user is not interacting with any objects or components.	Freehand gesture.
	Green sphere indicates the touch in handling CMM parts, such as the stylus for visual feedback to validate selections.	Pinch gesture.
	For scaling views in the measurement, particularly where a precise probe placement is needed.	Scaling gestures.
	For rotation of the stylus and part during the setup.	Rotation gesture.
	For manipulation of the stylus or workpiece.	Transition gesture.
	For interaction with the workpiece to select measurement points.	Tapping gesture.

Tab. 1: Hand gestures for CMM operations.

Voice Driven

The voice interaction is for the user speech input by adding keywords in MRTK to recognize and monitor the user speech commands. When the user issues a command, the AR's microphone captures the voice input, which is subsequently processed by the speech recognition system to convert it into text. The Natural Language Understanding (NLU) component then analyzes the input, identifies relevant keywords, and triggers the corresponding 3D animations and instructional overlays on the machine components using the toggle function.

When a speech command such as "Show components" issued by a user in training operations, all CMM components with their specific names are triggered as shown in Fig. 3(a). Additionally, another speech command prompts the AR headset to highlight the available objects as shown in Fig. 3(b). The real-time feedback of positioning the virtual object onto the CMM is illustrated in Fig. 3(c), when the speech command "Place object" is used.

(a) (b) (c)

Fig. 3: Voice commands operations: (a) CMM components, (b) measuring object, (c) placement feedback.

<u>Implementation of Proposed System:</u>

The system is designed into distinct training phases. After the object is tracked successfully, the 3D CMM model is rendered and overlaid onto the actual machine. The training phases for CMM operations, illustrated in Fig. 4, are integrated in the system. When the virtual object is superimposed onto the actual CMM, the user sees menu buttons as shown in Fig. 5, offering various options, including Machine Introduction, Stylus Management, Feature Measurement, Coordinate Selection, and Data Analysis.

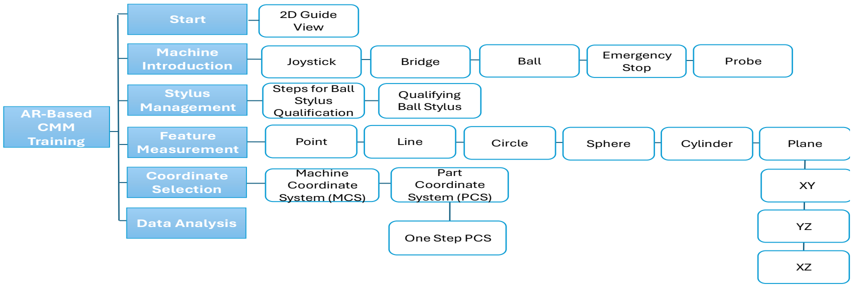


Fig. 4: Training modules for CMM operation.

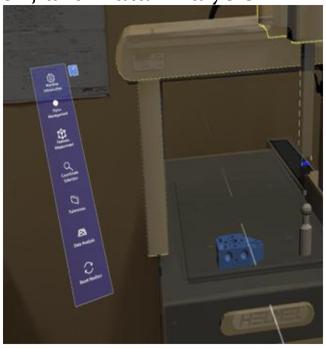
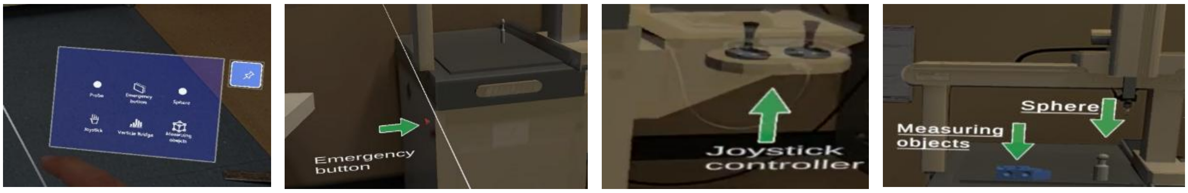


Fig. 5: User interface for CMM training.

CMM Introduction

Interactive menu-based buttons are utilized to guide the user in training through various components and functionalities of the machine. 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 Fig. 6.



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

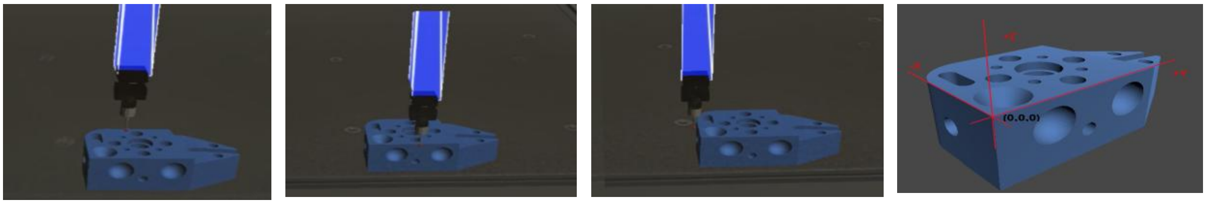
Fig. 6: CMM's component: (a) buttons, (b) emergency switch, (c) joystick, (d) object and sphere.

Stylus Calibration
Calibrating a CMM stylus is to ensure accurate dimensional measurements. This training employs a hybrid interaction method combining Unity's physics engine and hand-tracking technology to simulate the calibration process. The physics engine handles collision detection during stylus contact with the reference sphere, while hand-tracking provides visual feedback for pinch gestures. In stylus qualification process, the trainee first receives real-time visual guidance on how to qualify the stylus, as shown in Fig. 7(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 the number of remaining touches as shown in Fig. 7(b). Upon successful completion of the calibration procedure, the measured diameter of the stylus is displayed as depicted in Fig. 7(c).

(a) (b) (c)

Fig. 7: Stylus calibration: (a) instruction to qualify, (b) touch count, (c) measured diameter.

Coordinate selection
In the training, users are introduced to selection of coordinate systems for measurement and reporting tasks in Part Coordinate System (PCS) and Machine Coordinate System (MCS). MCS is a fixed, machine-based reference, while the PCS aligns with the part's geometry for accurate measurements. Trainees are guided to establish the PCS by tapping the stylus on designated datum targets, as illustrated in Fig. 8.



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

Fig. 8: PCS coordinate selection: (a) top plane, (b) front plane, (c) left plane, (d) PCS origin formed.

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.

<u>Results and Conclusions</u>
The AR-based CMM system is applied in training to measure geometric features. For example, to measure a circle, three points are tapped along a circular edge of workpiece with a stylus, allowing the system to compute the diameter as shown in Fig. 9 and Fig 10. For the cylinder feature measurement, six points are selected on the curved surface to decide the diameter as shown in Fig. 10 and Fig. 11.

The AR-based system of CMM operations provides advancement for the 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 a novel hand-tracking mechanism, enabling trainees to engage with CMM in a risk-free environment while performing CMM operations with efficiency. Critical tasks, such as the stylus qualification, part-coordinate selection, and feature measurement, are supported by using interactive and multimodal feedback, including visual and auditory cues.

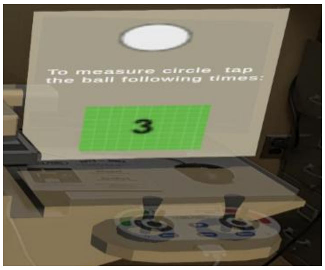


Fig. 9: Circle measurement procedure

Fig. 10: Measured circle diameter

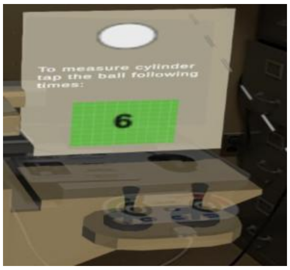


Fig. 11: Cylinder measurement procedure

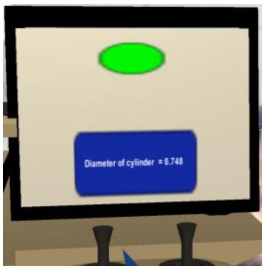


Fig. 12: Measured cylinder diameter

Therefore, the proposed AR-based CMM training system offers a significant improvement in user experience, usability, and trainee engagement. The further work is to conduct a user study to evaluate the effectiveness and perceived workload of the proposed AR-based CMM training system.

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