Title:
Virtual Reality-Based Training System of Coordinate Measuring Machine Operations

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Introduction:

Coordinate Measuring Machines (CMMs) are used in product quality control and assurance to verify dimensions, geometries, and spatial relationships of parts against design specifications. Essential for maintaining manufacturing integrity, CMMs help ensure that components meet requirements in industries like aerospace and automotive. The accuracy and reliability of CMM operations are fundamental for the quality and performance of final products [5]. A process flow of CMM operations is shown in Fig. 1.

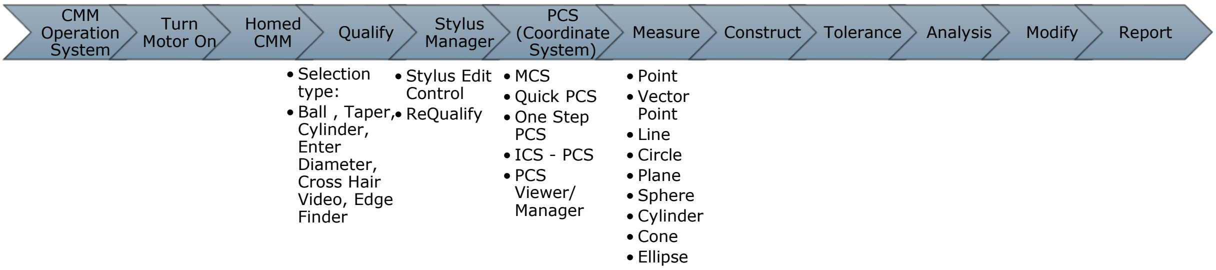

Fig. 1: Process Flow of CMM operations.

Traditional CMM operation training is challenged in the cost, access, and safety concerns, which needs interactions with costly equipment and strict safety protocols. Virtual Reality (VR) offers a transformative solution by simulating CMM functionalities in an immersive virtual environment, enhancing training efficiency and safety. Early VR developments focused on improving measurement accuracy through advanced modeling and error correction techniques, while later advancements have produced systems that closely mimic real machine behavior, with enhanced synchronization and movement monitoring [2]. Research indicates that VR training is more effective than traditional methods with precise simulations and collaborative training opportunities [4].

The objective of this research is to develop and evaluate a VR-based training system for CMM operations. The systematic approach is designed to equip trainees with a deep understanding of CMM operations, leveraging VR immersive capabilities for a safe, accessible, and cost-effective training alternative. The paper starts with a literature review on CMM training, analyzing past studies and identifying gaps. A new method is then proposed to enhance the effectiveness and efficiency of CMM training. It also explains the practical application of this method in real-world training. Finally, it summarizes key findings, discusses implications, and outlines future directions for CMM training research.

Main Idea.
Literature Review: CMM training has evolved with advancements enhancing both its efficacy and realism. Innovations have progressively led to the development of accurate, efficient, and user-friendly training environments. Historically, manufacturing metrology training relied on textual information and static imagery. These methods often fail to convey the complexity of dynamic machine operations adequately. Tab. 1 contrasts traditional training methods in terms of environment, risk, resources, learning experiences, challenges, and benefits, illustrating differences across various approaches. VR-based simulation training has emerged to offer immersive and interactive learning experiences. It prevents equipment damage and is scalable and replicable across various scenarios.

The development of CMM training has adopted innovative techniques to enhance training effectiveness and realism. Initial efforts involved haptic modeling to facilitate offline programming and collision-free paths with a tactile element to the training [5]. Subsequent advancements integrated neural networks to optimize CMM process training with artificial intelligence [1]. These improvements have brought new levels of automation and precision to the training systems. Moreover, the introduction of augmented reality has further enhanced the realism of training by merging physical machines with virtual environments and features like hand segmentation and motion analysis. These systems can simulate measurement processes and evaluate measurement uncertainties, closely mirroring real-world operations and increasing the quality of the training experience.

Method	**Environment**	**Risk**	**Resource Intensity**	**Learning Experience**	**Challenges**	**Benefits**
In-Person classroom training	Physical room	Low	Medium	Theoretical knowledge, limited practical experience	Limited hands-on experience, scheduling constraints	Structured learning, expert guidance
Hands-On Machine Training	On-site CMM	High	High	Direct practical experience, high realism	Risk of damage, high cost, limited accessibility	Real-world skills, immediate feedback
Manual Document Study	Self-study, anywhere	No	Low	Theoretical understanding self-paced learning	Lack of practical experience, self-motivation required	Flexibility, low cost, easy to update
VR-Based Simulation Training	Virtual environment	No	Medium	Immersive practical experience, safe, interactive learning	Technology dependency, initial development cost	Safe environment, scalable, replicable scenarios

Tab. 1: Existing CMM Operation Training Methods.

Despite these advances, challenges remain. Earlier methods were limited in their ability to offer a complete and integrated training solution for covering the entire measurement process [3]. The training of neural networks has been identified as a bottleneck due to slow training time affecting their real-time application. To address these limitations, recent research has explored shallow voxel-based representations to speed up the training process, albeit at the cost of memory efficiency [1]. Significant

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strides have been made in developing virtual CMM training systems, yet there is a pronounced gap in creating an all-encompassing simulator that fully embodies the scope of CMM functionalities. Technologies like CAD software have proficiently replicated complex geometrical designs, but integrating these with the dynamic operational aspects within a virtual setting remains incomplete. The domain of learner feedback and adaptive learning has also seen enhancements through machine learning techniques.

The research gap lies in the disparate nature of these advancements, where each tool excels in its specialized function but fails to contribute to a unified solution that encapsulates the multifaceted operations of CMM training. Unity offers a unique opportunity to bridge this gap by providing a versatile platform that integrates geometry, physics, behavior, and rule enforcement into a cohesive system, as shown in Fig. 2. By leveraging Unity capabilities, we can develop a comprehensive CMM training system that simulates the complex interplay of physical components and operational dynamics with an interactive learning interface [6].

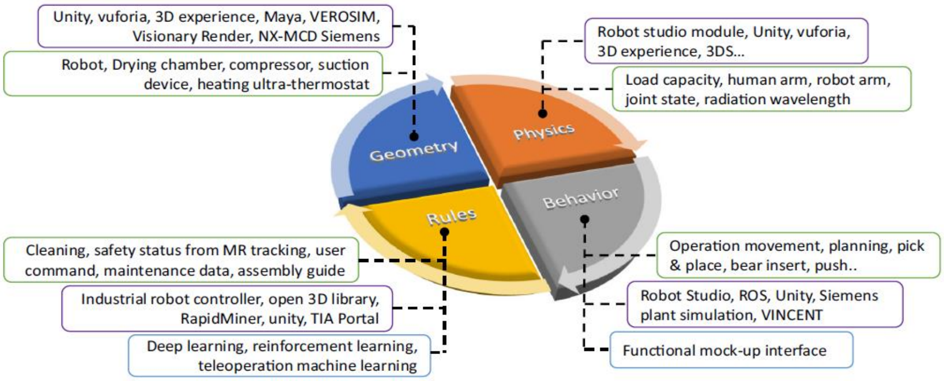

Fig. 2: Four pillars of training environment modeling: geometry, physics, behavior, and rules.

Proposed method for VR-based CMM Operations Training: The proposed system utilizes SolidWorks and Unity to create an immersive and realistic training environment. The system operates to handle intense graphics and CAD rendering across various platforms such as VR glasses, Mac OS, Android, and gaming consoles for wide accessibility and scalability. The development process is iterative, beginning with a prototype to test functionalities and focusing on enhancing simulation accuracy, refining the user interface, and optimizing system performance. Key features include scripting in C# in Unity for realistic physics simulation and a virtual screen that mirrors the display for training supervision, making it an engaging and comprehensive training tool. Contents of CMM operations are developed based on modules, as shown in Fig. 3.

Implementation of Training System: The training module is structured to describe required steps in the training program as shown in Fig. 3, starting from introduction to CMM and its parts, then moving to stylus qualification, coordinate system selection, data measurement and analysis.

Introduction to CMM: About CMM" step in the virtual training program provides an introduction to CMM and its parts like columns, probe heads, and controllers utilizing an interactive UI to provide an immersive experience that demonstrates the components and functions of CMM as shown in Fig. 4.

Stylus Configuration: In the "Stylus Configuration" step of the training, the Unity physics engine simulates the interaction between the CMM's stylus and object, using collision colliders for an interactive calibration exercise. Trainees virtually touch a stylus to a ball multiple times to record and analyze its dimensions using specific geometric formulas, teaching them to accurately calibrate and use the stylus in virtual CMM operations for precise dimensional analysis as shown in Fig. 5.

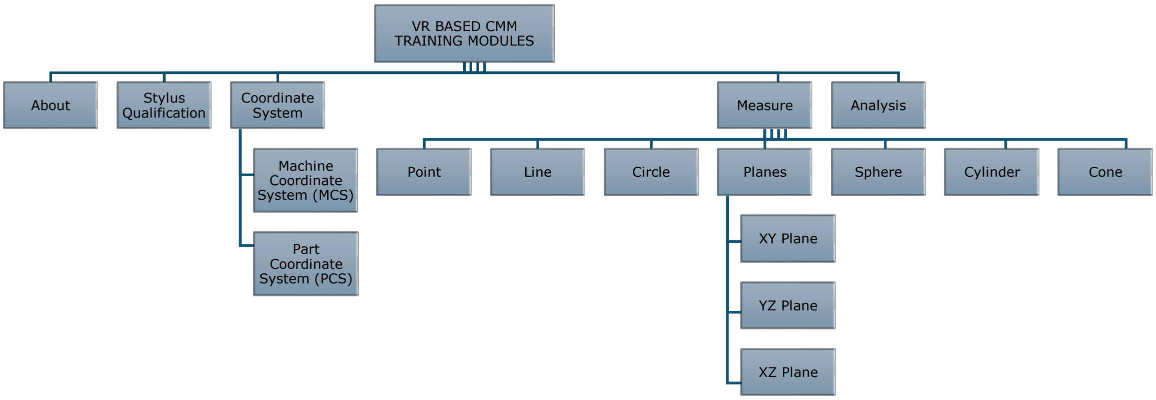

Fig. 3: Modules of CMM Operation Training.

Coordinate System Selection: The "Coordinate System Selection" step in CMM training introduces trainees to the Machine Coordinate System (MCS) and Part Coordinate System (PCS) as reference frames for accurate data interpretation and measurement.

Dimension Measurement: In the VR training program, trainees engage in dimensional analysis of various geometric features on a workpiece, such as points, lines, circles, planes, spheres, cylinders, ellipses, and cones. This process involves interactive virtual tapping, where colliders and mesh filters are used to precisely detect and render the exact point of collision to capture x, y, and z coordinates as shown in Figs. 6 and 7. These coordinates are then used to calculate specific dimensions by mathematical formulas for distance, radius, slant height, and more. For instance, measurements range from capturing simple points and lines to more complex forms like spheres and cones. This hands-on approach in the virtual environment, supported by the accurate coordinate capture at collision points, mimics real CMM operations. It allows trainees to directly apply theoretical knowledge to practical scenarios, enhancing their understanding and precision in measurement tasks.

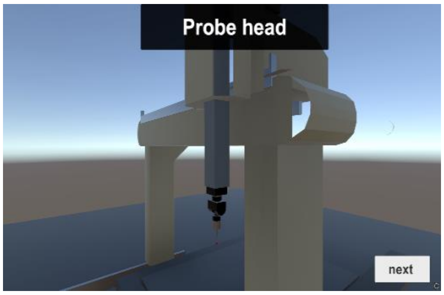

Fig. 4: Introduction to CMM parts.

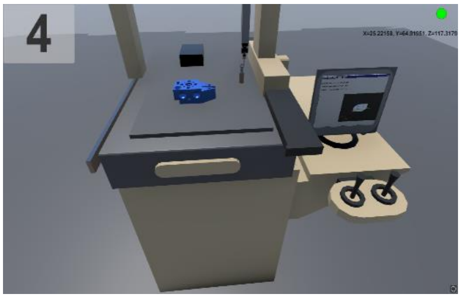

Fig. 5: Stylus Qualification Process.

Solution Evaluation: It evaluates the training feedback for the analysis of trainee performance, using data from dimensioning exercises to evaluate accuracy against tolerance requirements and identify potential errors. An automatic comparison feature assesses the accuracy of virtual measurements against actual data from the CAD model, helping users recognize discrepancies and refine their

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measuring techniques. This evaluative process is essential for reinforcing accurate measurement skills, ensuring that trainees' experience is effectively translated into real-world proficiency in CMM operations.

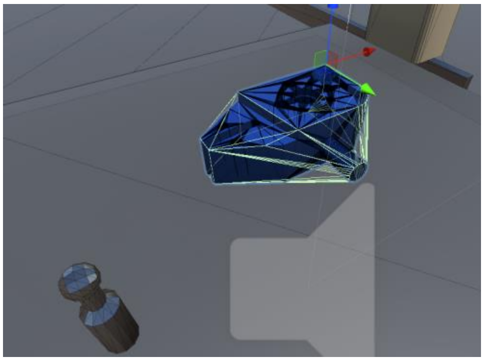

Fig. 6: Messing and Colliders.

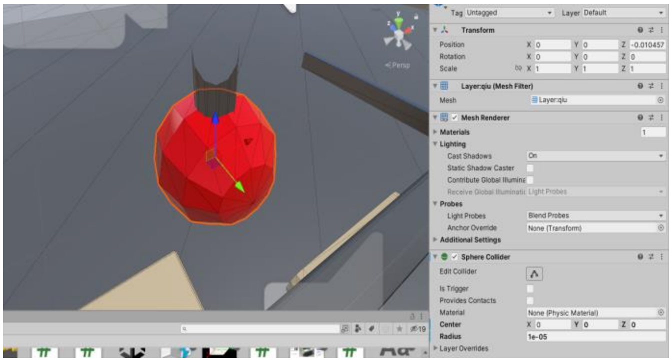

Fig. 7: Mesh Rendering on the probe.

<u>Conclusions</u>*:*

The VR-based CMM operation training system marks a significant improvement in precision measurement training. It integrates an interactive and comprehensive curriculum in a virtual environment, enhancing learning outcomes through engaging simulations. The system equips trainees with the necessary skills and knowledge for the high accuracy and efficiency in operating CMM, blending theoretical principles with practical applications.

Looking forward, the research solution will be enhanced by an augmented reality (AR) system with devices like HoloLens 2 for more tangible interactions and integrating haptic devices for more realistic simulations with tactile feedback. The effectiveness of the training system will be thoroughly assessed through user studies by comparing virtual and actual measurement data. Plans also include a multi-user system to support collaborative learning environments.

The ongoing enhancements and adaptations of this training system aim to establish a new way in CMM training, providing a cost-effective and scalable solution that meets the evolving needs of the manufacturing industry.

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