A Virtual Reality CMM Simulator for Technical Training in Geometric Dimensioning and Tolerancing

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Abstract: High-precision dimensional inspection and GD&T evaluation required for modern manufacturing can be achieved through Coordinate Measuring Machines (CMM). However, effective CMM operation demands significant practical expertise. Improper handling of CMM can result in probe damage, increased costs, and reduced operational efficiency. Traditional training processes are limited by minimal machine access, safety concerns, and a lack of hands-on practice. The development of psychomotor skills important for workplace readiness is hindered by these limitations. The design and implementation of a Virtual Reality-based CMM simulator integrated with real-time feedback and performance analytics is developed in this research study. The developed system replicates real-world CMM scenarios in an immersive virtual environment. Probe manipulation, measurement procedures, and GD&T evaluation without physical risk to the machines can be achieved through the VR-based CMM simulator. The developed simulator incorporates CAD model integration, coordinate system setup, and virtual probe control for capturing the virtual coordinates. Circularity assessment using the Maximum Distance Point Strategy and flatness measurement using the least squares methods are evaluated geometrically. The system architecture also supports guided and free probing modes. A 30 participant study demonstrated that VR-based training reduced the task completion time by 26.5 percent and improved measurement accuracy of geometric features such as circularity, flatness, and concentricity. Lower cognitive workload and better satisfaction by the participants were reported from NASA TLX and Likert scale results. The proposed VR-based simulator offers an interactive solution for CMM training to improve technical and vocational education.

Keywords: Metrology training, VR simulator, CMM operation, Geometric Dimensioning & Tolerancing, Technical education

I. INTRODUCTION

Modern manufacturing relies on Coordinate Measuring Machines for high-precision dimensional inspection and GD&T evaluation. Industries such as aerospace and automotive depend on CMMs to deliver high-quality products. However, significant hands on expertise and operator confidence is mandatory for effective operation of these machines. Improper handling can lead to probe damage, increased operational costs, and measurement errors. Moreover, the damages are expensive to repair and sometime lead to irreparable loss.

Traditional training methods often rely on physical CMMs, which are expensive and have limited availability in educational settings. Further challenges arise due to safety concerns and the risk of equipment damage. As a result, learners struggle to develop the psychomotor skills necessary for reliable CMM operation.

Recent improvement in virtual reality offer a promising alternative for technical training in various fields. VR provides immersive, risk free, and repeatable learning environments that can simulate complex machinery without physical consequences. A VR based training system for CMM operations was developed to deliver cost effective and scalable solutions for both industry and academia (Khan and Peng). Beyond CMM based applications, VR & augmented reality have been integrated with digital twin technologies in smart manufacturing, robotics training, electrical hands-on training and PLC training (Geng et al.). These developments demonstrate the higher scope of VR for hands on technical training in engineering and manufacturing contexts.

The effectiveness of VR in engineering education can be significantly improved when combined with established learning theories. A comprehensive review concluded that integrating educational theories with VR creates engaging and interactive learning experiences that enhance understanding and retention (Abbas Shah et al.). VR system can fill the gap between theoretical knowledge and practical application. Despite this potential, VR based simulators have not yet incorporated real time feedback, performance analytics, or psychomotor skill development frameworks. Furthermore, advanced GD&T evaluation methods such as the Maximum Distance Point Strategy for circularity and least squares for flatness have not been integrated into a VR training platform.

To address these gaps, this research presents the design and development of a VR based CMM training simulator that integrates real time feedback and performance analytics. CAD model import, coordinate system establishment, virtual probe control, and guided or free probing modes together form the proposed VR training system for geometrical features. Circularity, flatness, diameter, and concentricity are geometrically evaluated and implemented within the VR simulator. A 30-participant study was conducted to validate the VR training simulator against traditional training method.

The remainder of this paper is organized as follows. The literature review and theoretical framework are discussed in Section II. Section III describes the research design and system architecture. Section IV details the GD&T inspection algorithms. The results and discussion regarding the effect of VR on the participants are reported in Section V. Finally, the conclusion and future work are elucidated in Section VI.

II. THEORITICAL FRAMEWORK

To meet the accuracy demands of aerospace and automotive industries, various technologies and configurations are being developed to improve the operation of CMM (Hocken and Pereira). However significant scope remains for improvement in measurement of complex product geometries (Gąska et al.). Virtual models of CMMs have been developed to determine measurement uncertainty and predict errors, though challenges persist for advanced systems such as five axis measuring machines and optical CMMs (Gąska et al.). Ensuring measurement consistency across global supply chains though measurements at various location is a critical issue to be addressed. Effective and consistent CMM operation depends on number and placement of points to be captured (Saunders et al.). Despite this technological advances, effective CMM operation requires substantial hands-on expertise. CMM probe damage, increased costs, and inconsistent results occur mostly due to lack of proper training. Traditional technical training methods struggle to provide adequate practical experience due to restricted machine access and safety concerns. These barriers directly hinder the development of psychomotor skills essential for reliable CMM operation. An alternative approach to technical training is therefore needed. Virtual Reality offers a viable solution by delivering immersive, risk free, and repeatable hands on practice.

Virtual Reality has emerged as a powerful tool for enhancing engineering education by providing immersive and interactive learning experiences, though many VR studies lack a clear theoretical or pedagogical framework to guide their design and evaluation (Oje et al.). In vocational training, VR and augmented reality have been applied to welding instruction, where conventional methods are costly in terms of materials, time, and infrastructure, with the main contribution being the adaptation of virtual training functions to the psychomotor domain (Chan et al.). The integration of gamification with VR is being supported by multiple pedagogical theories and transforms traditional teaching into more engaging and an interactive learning experiences (Lampropoulos and Kinshuk). Immersive virtual reality is particularly suitable for learning environments that focuses on active learner engagement and practical application, such as efficient manipulation and constructive working skills (Conrad et al.). These studies demonstrate that VR can effectively support technical skill development across different vocational domains. The consistent finding across all applications is the critical importance of psychomotor skill for technical education.

The development of psychomotor skill is fundamental to technical and vocational education. Laboratory learning objectives in engineering span the cognitive, psychomotor, and affective domains, with discipline specific rankings offering better alignment for individual fields (Nikolic et al.). Theoretical knowledge is bridged with practical application through psychomotor skills. However, traditional teaching methods fail to address the industrial requirements such as precision, coordination, and adaptive learning. An Intelligent Tutoring System leveraging Extended Reality technologies was developed to provide real time feedback, error detection, and adaptive difficulty to personalize learning paths for psychomotor tasks (Barenji). The emergence of STEAM education has further embraced traditional understandings of skill acquisition by motivating hands on approaches to problem solving. This reimagination introduces the concept of psycho productive competency, which captures the interplay between psychomotor skills and cognitive emotional dimensions of learning (Okeke and Ramaila). VR based training systems for CMM operation must be designed with an explicit attention to the various psychomotor domains is confirmed from these literatures.

In summary, the reviewed literature confirms that CMM operation requires substantial psychomotor skillset which traditional training fails to develop effectively. Welding, maintenance, and design related training have proved to be effective through VR based training. However existing VR studies lack theoretical grounding in psychomotor domain and CMM training research. Furthermore, no prior work has incorporated real time feedback, GD&T algorithms, and performance analytics into a single VR CMM simulator, thereby motivating the present study. The following section describes the research design and system architecture developed to address these limitations.

III. RESEARCH DESIGN

A real-world inspection task in an immersive and interactive environment is designed in a VR based CMM training simulator. The developed system integrates three core components. They are CAD model import, controlling virtual probe, and real time GD&T computation. Figure 1 provides an overview of this proposed architecture.

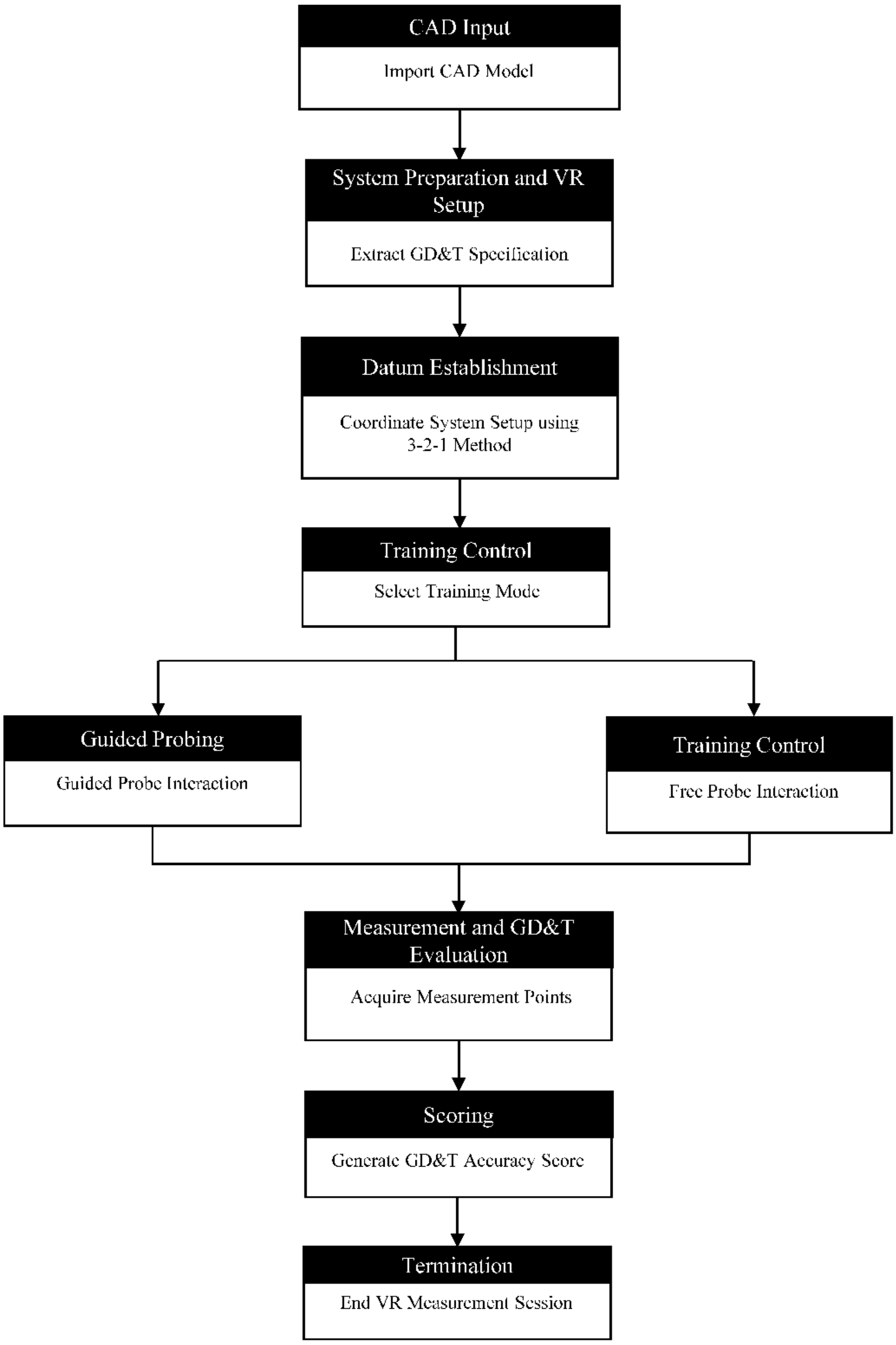
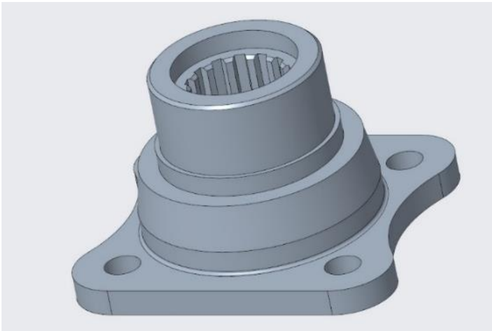


Figure 1 System Architecture Overview

Initially, the participant imports a CAD model into the VR environment. GD&T specifications are extracted from the model, and the datum is established. The virtual coordinate system is setup for the imported component using 3-2-1 method. The user selects the required training mode, either guided probing or free probing. In guided mode, the system will provide step by step instructions for probe interaction. The user shall independently maneuver the probe to capture the measurement points, in free mode. Once these points are captured, the system evaluates the measurement and computes the GD&T accuracy score of various features. The session is then terminated.

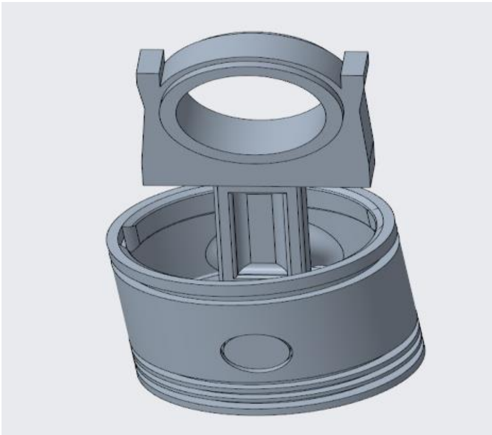
This simulator study makes use of a range of industrially relevant components such as flange, piston assembly and gear. Unique and distinct geometries such as flat surfaces, circular profiles, and concentric elements that require trained probing strategies are present in each component. The participants can practice flatness, circularity, and concentricity features without the need for importing multiple parts. The CAD models, as illustrated in Figure 2, were developed in Blender and imported to the virtual environment. An actual CMM workflow is replicated within this virtual environment.

(a)



(b)

(c)

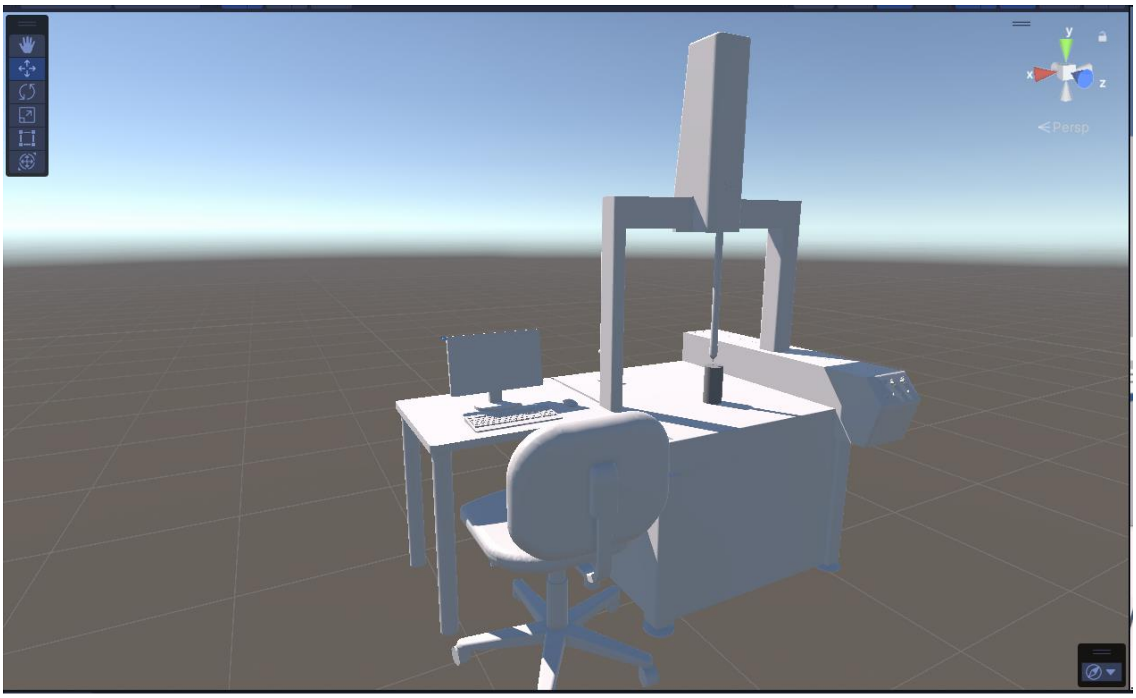


(d)

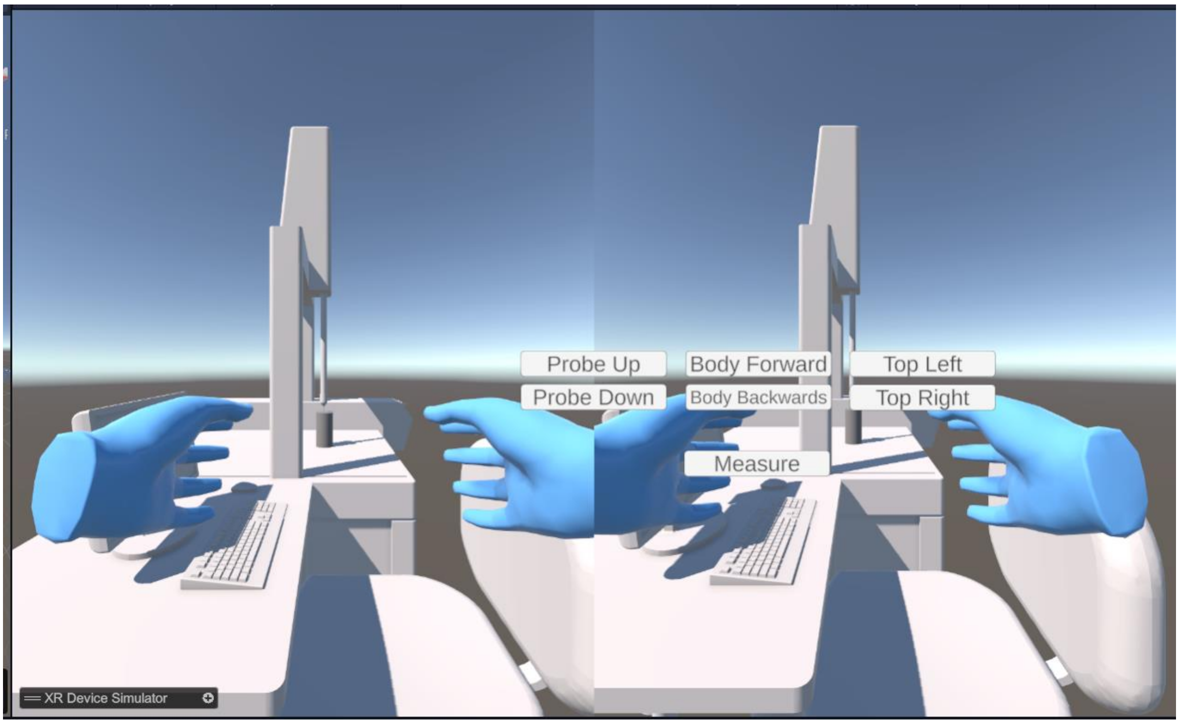
(e) (f)

Figure 2 Physical components and CAD model for measurement (a) and (b) Flange, (c) and (d) Piston assembly, (e) and (f) Gear

The VR environment developed in Unity software with interactive features is shown in Figure 3. The study was conducted using the Meta Quest 2 headset and its hand controllers for probe manipulation and menu interaction Figure 3(a) displays the initialized virtual CMM environment with the CAD model imported and the virtual probe ready for operation by the participants. Before pressing the measure button to capture points, the user shall move the probe up, down, forward, backward, and diagonally using the hand controller inputs. Figure 3(b) shows a participant actively interacting with the virtual CMM while wearing the VR headset and operating the controllers. This interface replicates the control logic of a physical CMM joystick panel. Thus without facing the risk of damage to the real CMM machine, operators can practice psychomotor coordination.



(a)



(b)

Figure 3 VR Environment developed in Unity (a) Initialized environment (b) User interaction

The VR based CMM simulator was designed as a replica of real inspection workflows. CAD import, coordinate system setup, guided and free probing modes, and real time GD&T evaluation are all integrated within the system. Environment and model creation in Blender ensured visual accuracy and interactive responsiveness. The system provided a pedagogically sound platform for vocational training, by adopting the logical sequence of physical CMM operation. Learners can practice till they are satisfied and make mistakes without real world consequences. The accuracy of such training ultimately depends on the mathematical methods used to interpret the captured points.

IV. DEVELOPMENT OF GD&T INSPECTION ALGORITHMS FOR VR-BASED CMM TRAINING

The mathematical formulations and procedural steps for diameter measurement, flatness evaluation, circularity assessment using the Maximum Distance Point Strategy (MDPS), and concentricity calculation are elaborated in this section. Each algorithm is elaborated to mirror real-world CMM inspection routines. It provides learners with transparent, step-by-step feedback within the virtual environment. The formulations presented for diameter, flatness, circularity, and concentricity follow established metrology practice. These equations were not modified for the virtual environment. The contribution of this work lies in integration of these methods within a VR environment. As the learner captures points using the hand controller, the corresponding GD&T value is computed and returned to the learner instantly. This immediate feedback is not available in conventional CMM training methods.

Diameter Measurement

The diameter measurement procedure begins with the capture of discrete virtual points on the shaft's outer curved surface. The center coordinates of the shaft are computed as the arithmetic mean of all measured x and y coordinates, as expressed in Equation (1):

$$x_c, y_c = \frac{\sum x_i}{n}, \frac{\sum y_i}{n} \tag{1}$$

Figure 4 presents the distribution of the captured points on the cross-section of the shaft.

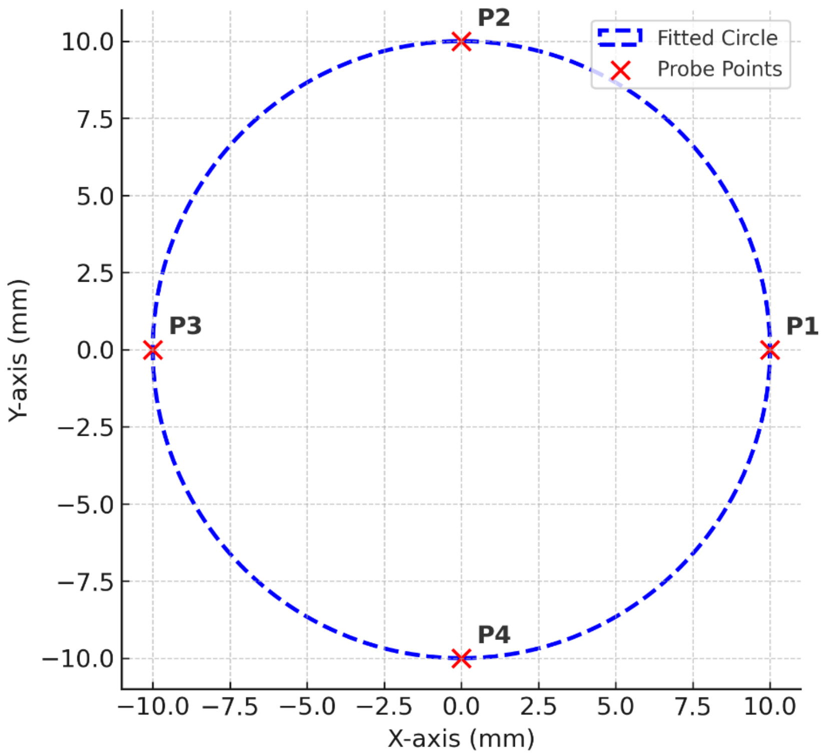


Figure 4 Measured Points of Shaft

The radial distance from the computed center (x_c, y_c) is calculated using Equation (2) for each virtually captured point (x_i, y_i),

$$r_i = \sqrt{(x_i - x_c)^2 + (y_i - y_c)^2} \tag{2}$$

The average radius R is then obtained from Equation (3), and the final diameter D is derived as twice the average radius, as mathematically denoted in Equation (4). The nominal shaft diameter based on average radial distance from the computed centers is calculated.

$$R = \frac{\sum r_i}{n} \tag{3}$$

$$D = 2R \tag{4}$$

Flatness Evaluation

Flatness defines the degree at which a surface deviates from an ideal plane. The flatness evaluation begins with the capture of n discrete points on the target plane. Equation (5) expresses the coordinates of the captured points,

$$P_i = (x_i, y_i, z_i), \quad i = 1,2, \dots, n \tag{5}$$

These captured points P serve as the input data for plane fitting and deviation calculation. To establish a reference plane that represents the surface to be measured, the least squares method is employed. Equation (6) defines the reference plane equation, and Equation (7) computes the vertical deviation (Z axis) of each measured point from this reference plane.

$$z = ax + by + c \tag{6}$$

$$d_i = z_i - (ax_i + by_i + c) \tag{7}$$

The fitted plane coefficients $a, b,$ and c that minimize the sum of squared deviations are collectively computed. Here Equation (6) represents the reference plane and Equation (7) quantifies the signed distance from each measured point P_i to that plane.

Finally, the flatness value is computed as the difference between the maximum and minimum deviations across all measured points, as mathematically denoted in Equation (8):

$$Flatness = \max(d_i) - \min(d_i) \tag{8}$$

The Equation (8) quantifies the total thickness of the zone that considers all measured points between two parallel planes. A smaller flatness value obtained from Equation (8) signifies a flatter surface.

Circularity Evaluation

Circularity is an GD&T parameter that measures how closely a measured profile approximates to a perfect circle. The evaluation procedures implemented in the VR-based CMM simulator follows the Maximum Distance Point Strategy (MDPS), which identifies three optimal points on the captured profile to build a reference circle.

The distance from any measured point $P_i(x_i, y_i)$ to an initial reference point $A(x_A, y_A)$ is computed as expressed in Equation (9),

$$d_i = \sqrt{(x_{\mathrm{i}} - x_A)^2 + (y_{\mathrm{i}} - \mathrm{y}_A)^2} \tag{9}$$

This distance metric help to identify the distribution of measured points relative to the selected reference point.

Figure 5 illustrates the geometric relationships between three selected points A, B, and C on the circular profile. The figure shows chord AB, the perpendicular distance from point C to chord AB, and the center $A(x_A, y_A)$ derived from the chord bisector method.

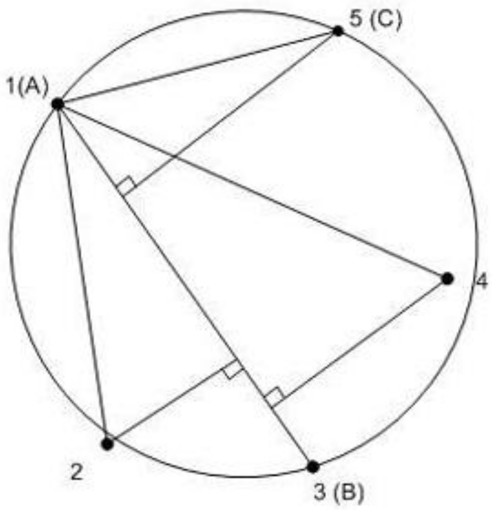


Figure 5 Representation of points A, B and C

To determine the optimal third point for circle fitting, the perpendicular distance from any point to the line joining points A and B is calculated using Equation (10):

$$d_P = \frac{|(y_B - y_A)x - (x_B - x_A)y + x_B y_A - y_B x_A|}{\sqrt{(y_B - y_A)^2 + (x_B - x_A)^2}} \tag{10}$$

C is the point that maximizes the value of d_P. It ensures that the extreme deviations of the measured profile are represented by the three points. As points A and B are established, the center coordinates (x_c, y_c) of the fitted circle is obtained using the chord bisector method. The chord bisector method is mathematically denoted in Equation (11):

$$2(x_B - x_A)x_c + 2(y_B - y_A)y_c = x_B^2 - x_A^2 + y_B^2 - y_A^2 \tag{11}$$

Equation (11) represent the linear equation derived from the perpendicular bisector of the chord AB by solving for the circle's center coordinate. Once the center coordinate is determined, Equation (12) calculates the radius of the fit circle. Moreover, Equation (13) expresses the radial distance 'R' from the computed center for all the measured point on the circular profile.

$$r = \sqrt{(x_A - x_c)^2 + (y_A - y_c)^2} \tag{12}$$

$$R_i = \sqrt{(x_i - x_c)^2 + (y_i - y_c)^2} \tag{13}$$

Finally, the circularity is computed as the difference between the maximum and minimum radial distances among all the measured points, as shown in Equation (14):

$$Circularity = \max(R_i) - \min(R_i) \tag{14}$$

This equation provides a single numerical value representing the deviation of the measured profile from an ideal circle. The smaller value from Equation (14) indicates higher circularity accuracy

Concentricity Evaluation

Concentricity is a GD&T parameter that quantifies the closeness between the center of the measured feature with the center of the datum feature. From the respective sets of measured points, the concentricity is evaluated through independent calculation of each center.

The center coordinates of the datum feature are computed as the arithmetic mean of all measured x and y coordinates on that feature, as expressed in Equation (15). Similarly, the center coordinates of the measured feature are obtained using the same averaging method, as mathematically denoted in Equation (16).

$$x_d, y_d = \frac{\sum x_i}{n}, \frac{\sum y_i}{n} \tag{15}$$

$$x_c, y_c = \frac{\sum x_i}{n}, \frac{\sum y_i}{n} \tag{16}$$

$$Concentricity = \sqrt{(x_c - x_d)^2 + (y_c - y_d)^2} \tag{17}$$

Once both centers are fixed, the concentricity value is calculated as the Euclidean distance between the two centers, as expressed in Equation (17). It provides a single numerical value representing the offset between the two centers. Here smaller values indicate better concentric alignment between the measured feature and the datum feature.

V. RESULTS AND DISCUSSION

The effectiveness of the VR-based CMM training simulator was evaluated through a controlled experimental study involving 30 undergraduate mechanical engineering students. Participants were divided equally into a control group. The control group received traditional CMM instruction using a physical machine. The experimental group is trained exclusively on the VR-based simulator. Both groups performed identical GD&T inspection tasks on similar component, and their performance was assessed using objective metrics, subjective workload, and perceptual feedback. Figure 6 presents the systematic evaluation architecture employed to ensure unbiased comparison.

The evaluation architecture, as shown in Figure 6, begins with matched group design based on CGPA range and prior VR exposure to ensure bias control. Participants were divided into a control group (traditional training) and an experimental group (VR-based training). The architecture then leads through an objective analysis encompassing numerical performance metrics and skill quantification. After this workload assessment using the NASA-TLX questionnaire and perception assessment via Likert scale survey are performed. Finally, performance scores were normalized to produce a standardized final score for enabling a fair comparison between the two training groups.

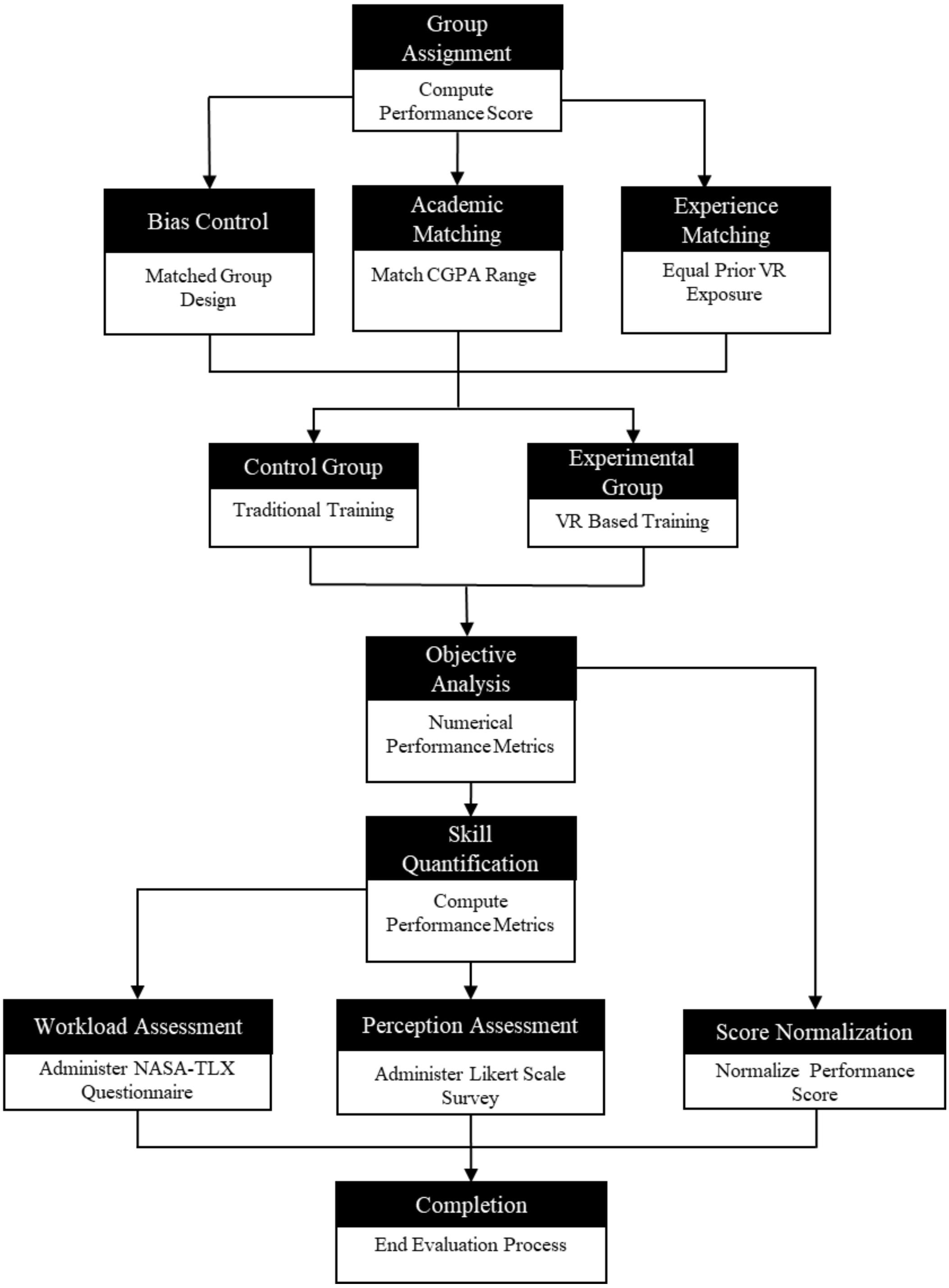


Figure 6 Architecture for the Evaluation

As summarized in Table 1, the student group was evenly distributed across both the control and experimental groups. Selection bias is overcome by uniform distribution. The students were classified into three academic tiers based on their CGPA: toppers (high CGPA), average performers (medium CGPA), and slow learners (low CGPA). Five students from each academic tier in each group are clubbed together. Fair distribution in gender was also maintained, with eight male and seven female participants in each of the group. This balanced distribution ensured that baseline academic aptitude and demographic factors were controlled.

Table 1 Student Distribution

Category	Without VR	With VR
Topper (High CGPA)	5	5
Average (Medium CGPA)	5	5
Slow Learner (Low CGPA)	5	5
Male	8	8
Female	7	7

The operational workflow of the VR-based CMM simulator follows a structured sequence of 4 stages. First, the learner has to select a component from the CAD model library, such as the step block, piston assembly, or helical gear. Second, the specific GD&T feature to be practiced is selected through the simulator's interactive interface. Third, the virtual probe is moved within the virtual environment to capture discrete measurement points depending on the selected feature. This feature mimics the three-dimensional point acquisition process of a physical CMM. Finally, the system computes the corresponding GD&T value, such as flatness, using the implemented least squares or MDPS algorithms, and displays the result with real-time feedback, as illustrated in Figure 7.

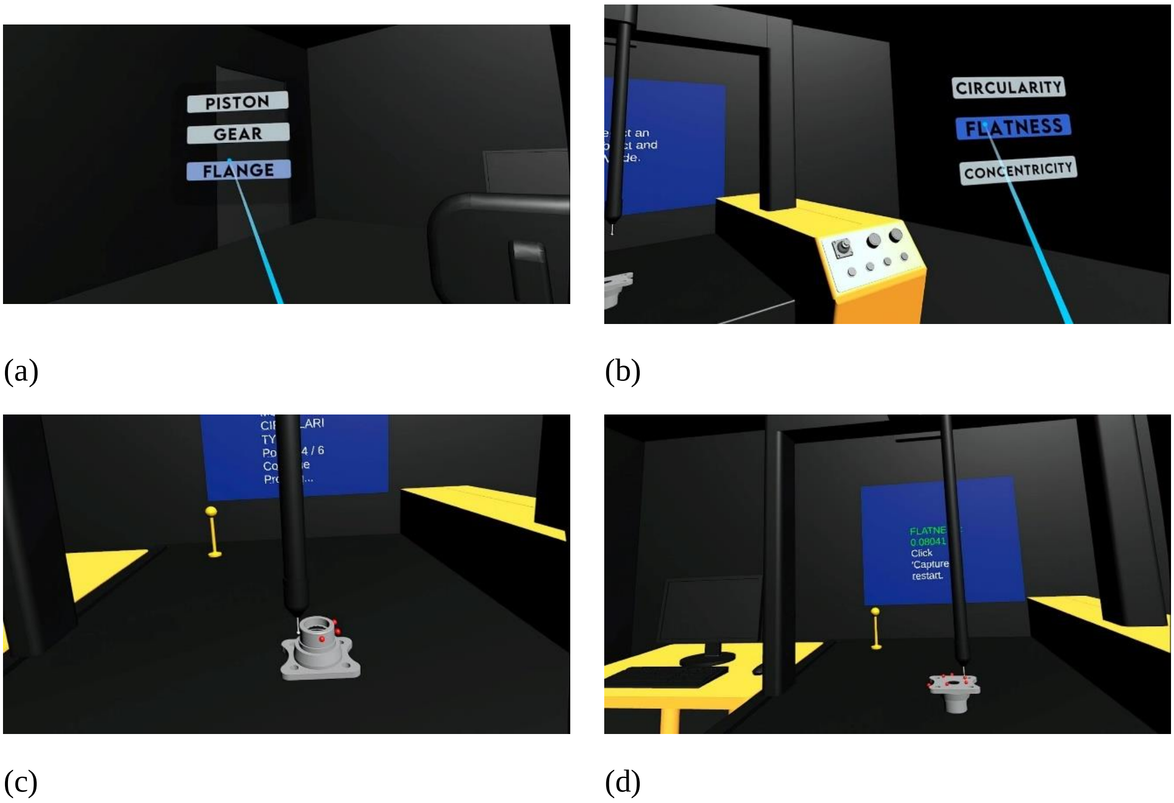


Figure 7 Stages involved in (a) Selection of Component (b) Selection of GD&T feature (c) Probe Capturing Points (d) Computation of Flatness value

An improvement in both operational efficiency and measurement precision among the VR trained group is observed. Task completion time dropped from 8.80 minutes in the control group to 6.47 minutes with VR training, reflecting a 26.5% gain in speed. This difference was statistically significant ($t = 3.65$, $p = 0.001$). For all three geometric tolerances, there was a significant reduction in measurement error. Circularity error fell from 0.036 mm to 0.017 mm ($t = 7.87$, $p < 0.001$), flatness error fell from 0.043 mm to 0.023 mm ($t = 8.40$, $p < 0.001$), and concentricity error fell from 0.041 mm to 0.019 mm ($t = 9.67$, $p < 0.001$). These results confirm that the improvements were not due to chance variation between groups. Overall, VR based training accelerated task execution along with an improved measurement precision. Statistical significance of this improvement is also reported in Table 2

Table 2 Independent samples t-test comparing performance with and without VR training

Metric	**Without VR** (Mean ± SD)	**With VR** (Mean ± SD)	**t value**	**p value**
Time (min)	8.8 ± 2.1	6.47 ± 1.7	3.65	0.001
Circularity (mm)	0.036 ± 0.008	0.017 ± 0.005	7.87	< 0.001
Flatness (mm)	0.043 ± 0.006	0.023 ± 0.006	8.40	< 0.001
Concentricity (mm)	0.041 ± 0.007	0.020 ± 0.005	9.67	< 0.001

From Tables 3 and 4, it can be interpreted that the participants exposed to VR based training are proficient in operating the CMM. The NASA TLX results in Table 3 indicate that VR training significantly lowered cognitive demand due to reducing effort and fear. These outcomes suggest that the virtual environment of VR allow participants to concentrate on developing hand eye coordination, probe maneuvering, and following measurement procedures without the fear of damaging expensive equipment. The VR environment has also helped the participants to overcome the fear of collision of probe with the components. Further, the Likert scale findings in Table 4 show that VR score is higher in ease of use, understanding, engagement, confidence, and satisfaction. Such improvements are mainly due to psychomotor skill acquisition. The CMM offers repeated virtual practice leading to muscle memory and procedural fluency. Together, these metrics demonstrate that immersive VR reduces cognitive friction and enhances learner motivation. They result in enabling effective skill acquisition of vocational and practical education.

Table 3 NASA TLX Results

Metric	**Without VR**	**With VR**
Mental Demand	75	55
Physical Demand	70	50
Temporal Demand	72	58
Performance	65	85
Effort	78	60
Frustration	80	52

Table 4 Likert Scale Results

Parameter	**Without VR**	**With VR**

Ease of Use	2.8	4.5
Understanding	3.0	4.6
Engagement	2.5	4.7
Confidence	2.9	4.6
Satisfaction	3.1	4.8

A consolidated and normalized view of overall performance is provided in Table 5, where all metrics are scaled between 0 and 1 for fair comparison. A significantly higher scores across every category: accuracy (0.91 vs. 0.70), time efficiency (0.89 vs. 0.63), GD&T proficiency (0.93 vs. 0.66), and final composite score (0.91 vs. 0.66) is achieved by the VR group. A 38% improvement in the final score indicates the pedagogical advantage of VR-based simulation over traditional training approach. Enhanced operator readiness along with minimal dependency on expensive lab equipment for technical and vocational institutions is attained.

Table 5 Normalized Performance Results

Metric	**Without VR**	**With VR**
Accuracy Score	0.7	0.91
Time Score	0.63	0.89
GD&T Score	0.66	0.93
Final Score	0.66	0.91

In summary, the VR based simulator has performed better than traditional training techniques across all metrics. The VR exposed group completed measurement tasks faster with minimal errors. They also show lower workload and higher satisfaction. These findings are significant for technical and vocational education. Integration of VR technology into metrology training curriculum is proved to be useful.

V. CONCLUSION

Trained and skilled CMM operators are in high demand to meet the quality requirements for modern manufacturing. Due to limited machine accessibility and safety concerns, traditional CMM training methods are ineffective. This paper has presented a VR based CMM simulator that addresses these challenges through an interactive, immersive & risk-free learning environment. CAD model import, coordinate system setup, and real time GD&T evaluation are all integrated within this virtual model. Algorithms for diameter, flatness, circularity using the MDPS, and concentricity were executed. A controlled study with 30 students showed that VR training reduced task time by 26.5 percent and improved measurement accuracy across all the considered GD&T parameters. NASA TLX and Likert scale results indicates lower cognitive workload and higher satisfaction by the participants. The findings confirm that VR based interactive simulation effectively develops psychomotor skills essential for technical and vocational education.

Despite these promising results, the current VR based simulation setup has limitations. Digital fatigue and discomfort for some participants were observed due to prolonged use of VR. Industrial trainers and technicians requires additional training and infrastructure support for wider adoption. Future work will consider the simulator to include other GD&T features such as perpendicularity and runout. Integration with other testing equipment like optical scanners and surface roughness testers is will also be useful for industries requiring skilled operators. Furthermore, incorporating augmented reality overlays onto physical CMMs could connect virtual practice and real machine operation. These enhancements will further strengthen VR based metrology training.

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