Virtual Reality-Based Training System of Coordinate Measuring Machine Operations

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Abstract. This paper introduces a Virtual Reality (VR)-based training system for Coordinate Measuring Machine (CMM) operations. It aims at an innovative training process of machine operations for cost-effective, scalable and accessible solutions in an interactive and engaging learning environment. A comprehensive VR model is developed to simulate CMM operations. The model incorporates detailed 3D representations of CMM operations with interactive user interfaces, texts, scripts, and physics for a realistic training experience. The system facilitates crucial operational tasks, such as the stylus configuration, setting of coordinate systems, and measurement of workpiece dimensions. The VR-based training system not only enhances the learning experience but also significantly improves the operational efficiency and precision of trainees, offering a viable solution for industries and academia. Details are discussed for the system development process, as well as applications of various interactive elements for comprehensive training in CMM operations.

Keywords: Coordinate measuring machine (CMM), Simulation, Virtual Reality (VR), Training, Machine Operations
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1 INTRODUCTION

Coordinate Measuring Machine (CMM) is an indispensable device in manufacturing, serving as the cornerstone for quality control and assurance. This instrument is pivotal for verifying the dimensions, geometries, and spatial relationships of manufactured parts against stringent design specifications. CMM is integral to maintaining the integrity of manufacturing processes, ensuring that the component meets the exacting standards required in industries ranging from aerospace to automotive manufacturing [9]. The accuracy and reliability of CMM operations are foundational to product quality, influencing the overall efficacy of manufacturing workflows and the final product performance [21][13].

A process flow of CMM operations, as indicated in Figure 1, begins with the initial step to power up the machine, ensuring that all mechanical components are energized and ready for operations. Once the motor is on and CMM is homed, the "Qualify" step involves calibrating the machine, often with a standard reference object, to ensure accuracy in measurements. The "Stylus Manager" phase is dedicated to choosing the appropriate stylus for measurements and verifying its condition and alignment. Then, in the "PCS" stage, the coordinate system is selected and set, which could be either the machine coordinate system or the part coordinate system, depending on the specific measurement requirements. In the "Measure" step, the actual measurement of the workpiece occurs, where the CMM collects data points on specified features. Following the measurement, the "Construct" phase may involve creating geometric constructs from the measured points, lines, or surfaces. The "Tolerance" step involves comparing the measurements against predefined tolerances to determine if the part meets the specified quality standards. The "Analysis" stage is where the data are further examined to understand the measured features' properties and dimensions, and any deviations from the expected results. If deviations are identified or if there are aspects of the workpiece that need alteration, the "Modify" stage allows for adjustments or corrections to be made to the measurement process or to the part programming. Finally, the "Report" phase concludes the process by generating a detailed report that documents all measurements, analyses, and any modifications made. This report serves as a record of the inspection for quality assurance and verification purposes [2].

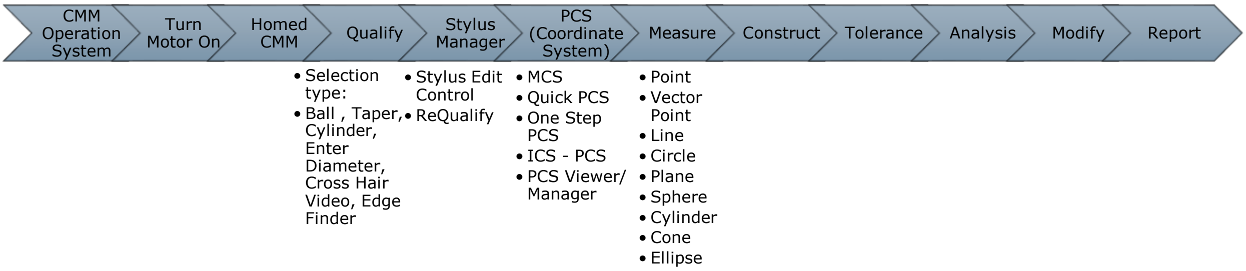


Figure 1: Process flow of CMM operations.

Challenges of the traditional CMM operation training are multifaceted with issues of cost, access, and safety [29]. Traditional training methods rely on a direct interaction with costly equipment and real workpieces, present logistical and financial barriers that limit training accessibility and elevate risks of mishaps. Furthermore, the necessity for safety protocols adds another layer of complexity to the training process.

Virtual Reality (VR) has emerged as a transformative solution to these challenges, presenting an innovative pathway to comprehensive CMM training. VR training systems for machine tools utilize cutting-edge technology to simulate the functionality and operations of CMM, allowing trainees to immerse themselves in a virtual realistic environment [11][16].

Early developments in VR-based training systems for CMM operations sought to harness the emerging capabilities of VR to enhance the precision and user-friendliness of the complex measurements. Notable efforts include the creation of a virtual model for CMM, leveraging homogeneous transformation matrices for accurate structural modeling and implementing the multi-stage error correction to refine measurement accuracy [8]. Another contribution is the development of a VR-based training system for machining operations of a milling tool, incorporating features like interference checks and the realistic reproduction of machined shapes [4]. These systems lay the groundwork for VR training environments, emphasizing safety, precision, and an immersive learning experience for operators.

These VR-based systems have evolved to closely mirror the behavior of actual machines, with enhancements in synchronization, movement monitoring, and realistic reproduction of operation outputs [17]. Research indicates that VR-based training can rival or even surpass traditional training methods in efficacy, fostering superior learning efficiency and retention [3][24]. The potential for future VR training systems includes more accurate machine simulations, heightened interactivity, and the possibility for distributed, collaborative training experience.

The objectives of this research are to develop, implement, and evaluate a comprehensive VR-based training system for CMM operations. Our proposed model unfolds in four distinct stages, beginning with an introductory overview and fundamental principles. Subsequent stages involve detailed probe/stylus qualification and precise selection of the coordinate system to maneuver and culminate in practical measurement exercises on a virtual workpiece, which is the same as the real product for performing measurements and is designed to closely mimic real-world dimensioning tasks. This systematic approach aims to equip trainees with a thorough understanding and proficiency in CMM operations, leveraging the immersive capabilities of VR to provide a safe, accessible, and cost-effective training solution.

The paper contents are organized as follows. Section 2 delves into the existing research, presenting a thorough literature review that critically examines previous studies, highlights advancements, and identifies gaps in the current knowledge surrounding CMM training methodologies. Section 3 introduces the proposed method for CMM training, where we unveil an approach designed to enhance the efficacy and efficiency of training programs in this domain. Section 4 details the practical application of our proposed method, illustrating the step-by-step process of bringing the theoretical framework to life within a functional training system. Finally, Section 5 summarizes the key findings, discusses the implications of our research, and suggests avenues for future exploration in the realm of CMM training systems.

2 LITERATURE REVIEW

In the evolving process of CMM training, significant strides have been made through different techniques to enhance the efficacy and realism of training processes [27]. The journey towards improving CMM training has seen a progressive series of innovations aimed at creating an accurate, efficient, and user-friendly training environments [12][31].

Training in the manufacturing metrology has historically been constrained by limitations of traditional methods [22]. The conventional pedagogical approach relies on the textual information and static imagery to convey procedural knowledge, which is inadequate for comprehending multifaceted and dynamic machine operations. Traditional training methods are often contrasted in terms of environment, risk, resource, learning experience, challenges, and benefits, as shown in Table 1.

Training Method	Environment	Risk	Resource Intensity	Learning Experience	Challenges	Benefits
In-Person Classroom Training	Physical classroom	Low	Medium	Theoretical, limited practical experience	Limited hands-on experience, Scheduling constraints	Structured learning, expert guidance
Hands-On Machine Training	On-site with actual CMM	High	High	Direct practical experience, high realism	Risk of damage, High cost	Real-world skills, immediate feedback
Manuals & Document Study	Self-study, anywhere	No	Low	Theoretical, 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	Technology-dependent, High development cost	Safe environment, Scalable

Table 1: Existing CMM operation training methods.

In-person classroom training, one of the most longstanding methods, takes place in confines of a physical classroom, presenting the low risk but also limited hands-on experience [25]. Despite the structured learning environment and expert guidance available, this method faces challenges such as scheduling constraints and a disparity between theoretical knowledge and practical application.

Hands-on machine training offers the most direct experience, situated on-site with actual machinery [5]. It provides the highest level of realism and immediate feedback, which is crucial for developing real-world skills. However, this method is resource-intensive and presents higher risks, including potential damage to expensive equipment and inherent dangers of novice operators handling complex machinery. Accessibility is also a challenge [20].

Self-study through manuals and documentation offers a low-risk, low-resource alternative that allows for self-paced learning [26]. While it excels in flexibility and ease of updating material, it lacks in providing practical experience, and self-motivation becomes a key factor for the learning success.

VR-based simulation training emerges as a modern solution, leveraging a virtual environment to create an immersive and interactive learning experience [10]. VR-based training eliminates the risk of physical harm or equipment damage and presents a scalable and replicable scenario for a wide range of situations.

Initial efforts in CMM training focused on leveraging haptic modeling techniques to facilitate off-line programming and generate collision-free probe paths [23]. This approach was groundbreaking, providing a tactile dimension to virtual training that allowed users to experience a more hands-on learning process. These techniques were instrumental in laying the groundwork for subsequent advancements in CMM training methods. Building on this foundation, researchers explored the integration of neural networks with conditional attributes specifically tailored for the selection of CMM [18]. This method marked a significant leap forward, utilizing the power of artificial intelligence to optimize machine selection processes based on a set of predefined criteria.

The application of new technologies has introduced a level of automation and intelligence in training systems that was previously unattainable, enhancing both the efficiency and precision of the training process [2][6]. However, these methods depend on technology and costs associated with developing and implementing VR systems [32]. Despite these challenges, VR-based training offers a safe environment that can be tailored to various learning objectives and competency levels. Moreover, gamified learning platforms introduce elements to engage users for improved retention and motivation [19].

Further advancements were achieved with the introduction of augmented reality into CMM training environments [1][21]. This innovative approach sought to merge physical details with the virtual training landscape, employing techniques such as the hand segmentation, motion analysis, and model rendering [15]. This blend of real and virtual elements brought an unprecedented level of realism to CMM training, allowing for an immersive and interactive learning experience that closely mirrors real-world operations. In a bid to simulate the measurement process with even greater fidelity, a CMM training system was developed that supports not only the simulation of measurement processes but also the evaluation of measurement uncertainty [14]. This system was capable of interfacing directly with physical CMM controllers, further blurring lines between virtual training environments and actual machine operations. By simulating real-world scenarios and incorporating uncertainty evaluation into the training process, this approach provides a comprehensive training solution for a wide range of operational contingencies.

Therefore, the manufacturing metrology training stands at an intersection where traditional methods are being augmented, and sometimes replaced, by advanced technologies. VR technologies offer not just improved educational outcomes but also greater accessibility and safety for learners.

Despite these advancements, challenges remain. Earlier methods, while innovative, were limited in their capability to offer a complete and integrated training solution that can encompass the entire measurement process. Furthermore, the training of neural networks was identified as a bottleneck, with slow training impeding their applications in real-time scenarios. In response to these limitations, recent research has pivoted towards exploring shallow voxel-based representations to accelerate the training process, although it requires a compromise in terms of the memory efficiency. Through this progressive series of research and development efforts, the field of CMM training has continually evolved. Each innovation is built in pushing boundaries of virtual training environments and bringing us closer to a fully integrated, efficient, and realistic training solution for CMM operations.

Although significant strides in the development of virtual CMM training systems, research reveals a pronounced gap in creating an all-encompassing simulator that thoroughly embodies the full scope of CMM functionalities. While existing technologies such as CAD software have proficiently replicated the complex geometrical designs of CMM components, their integration with the dynamic operational aspects of the machines within a virtual setting remains incomplete. The realistic simulation of CMM physics has seen contributions from tools like Robot Studio and Vuforia; meanwhile, operational behavior and movement strategies have been addressed using ROS, Unity, and Siemens PLM software [7][31]. Additionally, the domain of learner feedback and adaptive learning has been enhanced through machine learning techniques [30].

However, the main research gap lies in the disparate nature of these advancements. Each tool excels in its specialized function but does not contribute to a unified solution that encapsulates the CMM multifaceted operations in a singular, immersive training module. Geometry, physics, behavior, and rules are main pillars of building a virtual training environment as shown in Figure 2.

Each of these pillars plays a crucial role in mirroring the complexity and interactivity of the real process in a controlled digital setting. Geometry involves the creation of 3D models that represent the physical objects in the training environment. Geometry is foundational, as it visually constructs everything trainees will interact with, from simple tools to complex machinery. Accurate geometrical representations ensure that the virtual environment closely resembles the physical world, enhancing the realism and efficacy of the training, Physics governs the interaction between 3D objects in the training environment. It simulates real-world laws like gravity, friction, and material properties, dictating how objects move, collide, and behave when forces are applied. This realism is vital for practical training, where understanding the physical interaction between tools and materials is necessary for skill acquisition.

Rules set the boundaries and guidelines for the training scenarios operation, aligning the virtual environment with real-world scenarios and standards. This includes operational procedures, safety protocols, and performance criteria. By embedding these rules into the training environment, trainees can learn not just how to perform tasks, but also the correct and safe way to conduct them, adhering to prescribed standards and regulations. The behavior component focuses on the dynamic aspects of the training environment and how interactive elements respond throughout the learning process. This includes the adaptability of the system to the trainee's actions, feedback mechanisms, and the progression of scenarios in response to user input. Behavior modeling is crucial for creating an engaging and educational experience, allowing trainees to experiment, make decisions, and learn from the outcomes of their actions.

These four pillars, geometry, physics, behavior and rules, constitute the core of a well-rounded training environment. They ensure that virtual training scenarios not only achieve visual accuracy and physical realism but also adhere to necessary operational protocols while displaying dynamic, interactive behaviors. This holistic modeling approach greatly enhances the learning experience, preparing trainees for real-world applications by immersing them in scenarios that accurately reflect the complexity and demands of their specific fields.

Modeling software like SolidWorks and AutoCAD are excellent for creating 3D models, but they lack capabilities to simulate the physical behaviors of objects under real-world forces such as gravity and inertia. For these purposes, specialized software like Robot Studio Module and Vuforia are employed to handle physics simulations [33]. Defining how objects interact or establishing operational behaviors typically involves advanced tools like ROS and Siemens PLM software.

With technological advancements, there is a need for systems that simulate and adapt autonomously. Unity emerges as a versatile platform capable of integrating geometry creation, physical simulation, behavior definition, and rule enforcement all in one environment [28]. Unity allows for the application of advanced AI techniques like deep learning and reinforcement learning, empowering the system to autonomously define rules and make decisions. This integrated platform can synergize various elements into a cohesive system, enabling the development of a CMM training system that accurately simulates the complex interplay of physical components and operational dynamics, complete with an interactive learning interface.

Despite challenges such as setting up precise collision detection and adjusting coordinate values from arbitrary transform scales, Unity is invaluable for creating realistic training environments that can adapt to any platform for enhancing the accessibility and effectiveness of training modules. By harnessing Unity's expansive capabilities, we can revolutionize CMM training, providing a holistic educational tool that adeptly prepares learners for the intricate realities of CMM operations.

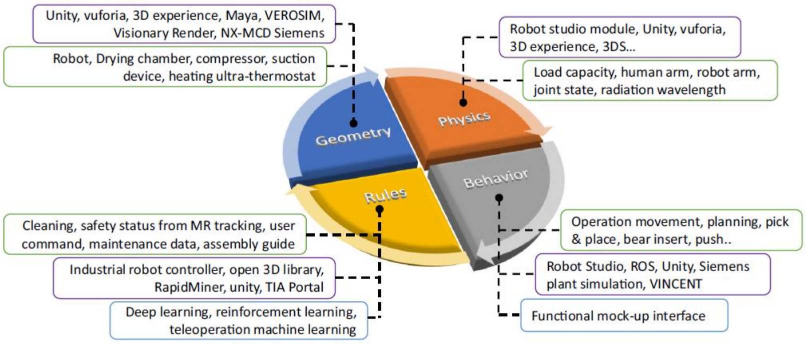


Figure 2: Four pillars of training environment modeling: geometry, physics, behavior, and rules.

3 PROPOSED METHOD FOR CMM OPERATION TRAINING

A VR-based CMM training system is proposed to encapsulate an integrative approach that leverages cutting-edge hardware and software. The system is structured to ensure an immersive, realistic, and educational training experience using SolidWorks and Unity tools. A VR-based operation training environment is built, including a CMM model and training part, as shown in Figures 3 and 4, respectively.

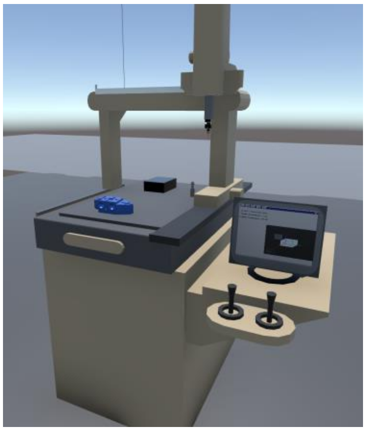


Figure 3: CMM model.

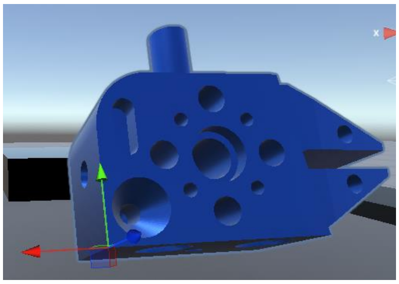
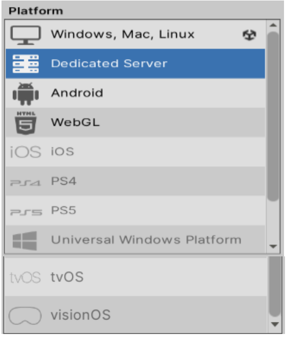


Figure 4: Training part.



Platform
Windows, Mac, Linux
Dedicated Server
Android
WebGL
iOS
PS4
PS5
Universal Windows Platform
tvOS
visionOS

Figure 5: Model's platforms.

3.1 Hardware Integration

The VR training system is equipped with a GTX 1660TI GPU and an i7 10th generation processor, ensuring it can handle the graphics-intensive demands of running high-quality simulations and rendering detailed CAD models efficiently. The system, running simulations on a similar PC setup, loads projects in Unity within about 10 seconds. While systems with lower specs might face longer load times, those with higher specs can load the projects faster. Once loaded, the system allows for seamless navigation through the virtual environment using a keyboard and mouse, akin to video game interactions.

In Unity, we can adjust the build's quality and resolution to optimize performance according to the system's capabilities. Currently, our windows application for training operates efficiently without the need for such adjustments, ensuring a high-quality, responsive training environment with minimal lag or latency. This setup provides an effective and smooth operational experience for users.

Using the Unity engine, the training system is designed for adaptability to other platforms. The versatility of Unity facilitates the operation of the VR system on various devices, including VR glasses for an immersive experience, Mac OS for wider accessibility, Android for the mobile integration, and gaming consoles such as PS4 or PS5 to tap into their robust processing capabilities. This cross-platform operability ensures that our VR training system can be easily used across different hardware ecosystems, making it a highly scalable solution for CMM training needs as shown in Figure 5.

3.2 Software Development

The system development commences with the integration of SolidWorks CMM models and Unity simulation functions. The CMM model is exported from SolidWorks in a format conducive to Unity compatibility and then imported into the Unity project. A significant portion of the development effort is allocated to script in C# in Unity to simulate physics accurately, manage user interactions, and implement a user interface (UI) for an intuitive and engaging learning experience.

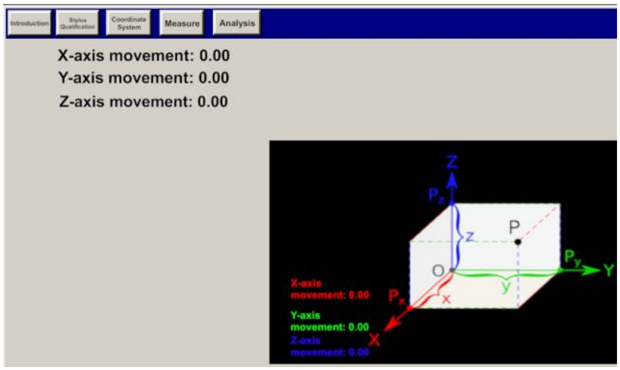
3.3 Development Process

The development of the CMM training system follows an iterative approach, beginning with the creation of an initial prototype. This prototype is essential for testing the fundamental capabilities of the system, such as the importation of CAD models into Unity and the initial interaction mechanisms. The core functionalities are carefully analyzed to ensure they met standards for an authentic CMM experience.

As the development progressed, we focus on enhancing the simulation accuracy, continuously refining the user interface and user experience (UI/UX) for intuitive operations, and optimizing performance for user interactions. A virtual screen is a pivotal feature of the system. It mirrors the display onto an external monitor, offering an alternative view for those supervising or assisting in the training as shown in Figure 6.

By pressing the "M" key, users can toggle this virtual screen to a full-screen mode for an in-depth analysis of the details displayed. This screen not only showcases options available for the selection but also provides real-time readouts of coordinates being measured, the active coordinate system, and the type of dimensions currently in use. The user interface is designed with the foresight that users may need to transition back and forth between the virtual environment and the full-screen display for a more detailed comprehension of their actions. A press of the "M" key allows users to re-enter the interactive VR space seamlessly, promoting a smooth and uninterrupted learning experience.

Throughout the design process, we embrace the user feedback and utilize it to drive the development cycle, ensuring that each iteration brought users closer to the system that was not only functionally rich but also user-centric in its operation. The result is a versatile and effective training platform. These simulations can be applied to any type of CMM model in any platform and easy to iterate and add new functions based on technology advancement or user feedback. Moreover, whenever the probe makes contact with the workpiece, the event is indicated by the illumination of a green light in the top-right corner of the VR environment as shown in Figure 7. This visual cue is an integral part of the system feedback mechanism, signaling successful data acquisition. Upon this indication, the exact value of coordinates at the point of contact is captured. These coordinates are crucial as they serve as the data points of all measurements. The system is designed to automatically log and display these values for the trainee who can then use them to perform the necessary calculations for dimensional analysis. This feature ensures that trainees receive immediate, unambiguous confirmation of each successful measurement, reinforcing the learning process and enhancing the accuracy of the training experience.



X-axis movement: 0.00
Y-axis movement: 0.00
Z-axis movement: 0.00

Figure 6: Virtual screen view.

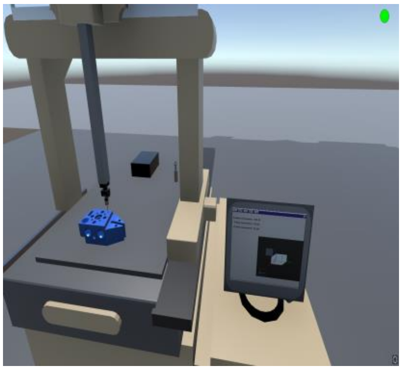


Figure 7: Probe collision detection.

3.4 Operation Modeling

Comprehensive educational contents of CMM operations are developed based on modules as shown in Figure 8. The details are described in Section 4.

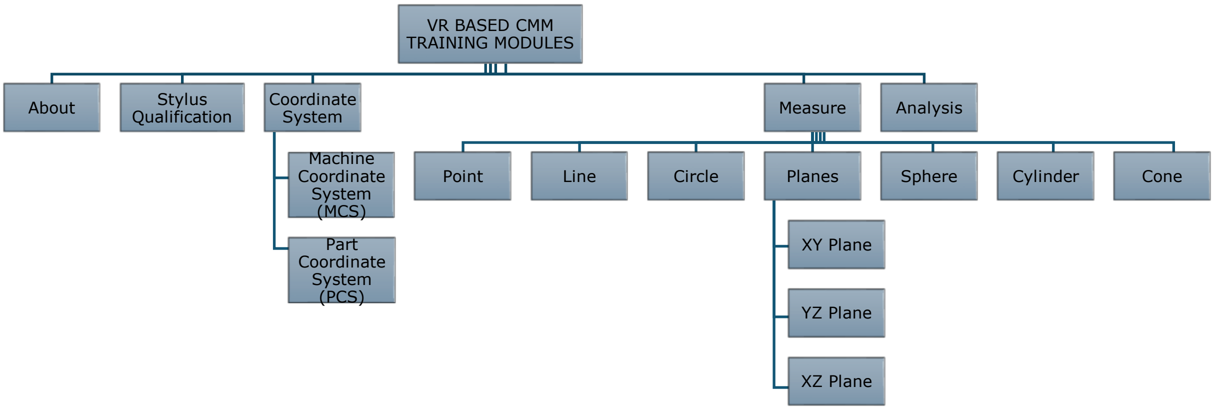


Figure 8: Modules of CMM operation training.

4 IMPLEMENTATION OF THE TRAINING SYSTEM

The modules are structured to describe required steps in the training program as shown in the top blue bar of Figure 6, starting from introduction to CMM and its parts, then moving to the stylus qualification, coordinate system selection, data measurement and analysis.

4.1 Introduction to CMMs

The "About CMM" step of the virtual training system is for a comprehensive introductory, where trainees are acquainted with fundamental concepts and elements of CMM. It utilizes the interactive capabilities of UI to provide an immersive educational experience that visually and contextually demonstrates components and functions of CMM. In this introduction, the virtual environment allows trainees to explore each segment of CMM, for example, the base serves as the CMM foundation; the column supports the bridge and probe; the bridge itself spans the base and allows the probe to move across the surface of the object being measured; and the probe is the critical element that physically contacts the part to take measurements. For example, Figure 9 shows the enlarged view of a few major elements in the CMM. Each component is virtually rendered and can be interactively examined to understand its mechanical purpose and contribution to the overall precision of the CMM system.

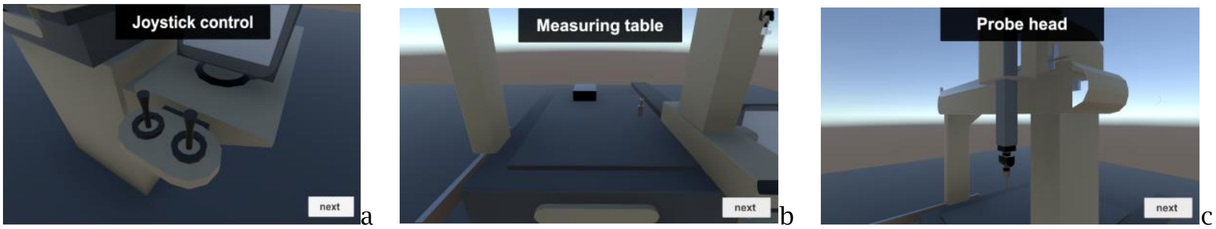


Figure 9: Introduction to CMM parts: (a) Joy stick control, (b) Measuring table, (c) Probe head.

Furthermore, this step delves into the operational theory behind CMM, explaining the complex machine for providing highly accurate and repeatable measurements. Trainees are guided through the process of understanding the physical dimensions of a part into digital data points analyzed for quality control purposes. Trainees can engage with each component, receiving real-time information on its significance and operation, which promotes an engaging learning environment. This method of presentation facilitates a deep understanding of CMM capabilities and applications before trainees proceed to more practical aspects of the training.

By using virtual elements to depict the physicality of CMM, the "About CMM" sets a foundation for the subsequent modules of the training system. It ensures that trainees are well-prepared with the necessary background knowledge to appreciate the complexities and nuances of working with CMM in a virtual space, eventually translating these skills into real-world proficiency.

4.2 Stylus Configuration

In the "Stylus Configuration" step, Unity's physics engine is utilized to simulate the interaction between the CMM's probe (stylus) and the object being measured. Employing collision colliders provides an interactive environment where trainees can virtually touch the probe 5 times against a ball to simulate the act of taking measurements, as shown in Figure 10 after the first touch, where we record the coordinates and the touch count decreases from 5 to 4. This process employs Unity's "TapToGetValue" feedback system, a mechanism that debugs and presents the values of X, Y, and Z coordinates upon each contact between the stylus and the virtual object.

This module is designed to teach trainees the proper technique for stylus calibration through a practical exercise. The trainee touches the stylus to the ball five times at different points, and each contact point will be used to determine the probe's diameter and radius. This hands-on approach enables the trainee to learn the stylus configuration. The mathematical foundation of this exercise is based on the general equation of a sphere as follows.

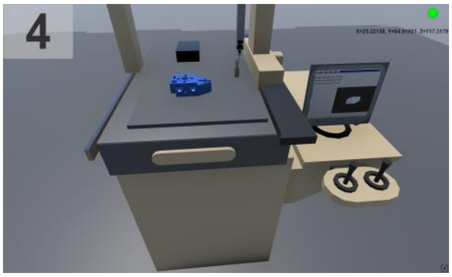
$$x^2+y^2+z^2+Ax+By+Cz+D=0 \tag{4.1}$$

where (x, y, z) are coordinates of a point on the sphere surface, A, B, C, and D are constants that determine the position and size of the sphere. Once the sphere's equation is established, the center and radius of the probe are calculated using Equations (4.2) and (4.3).

$$\text{Center}(h, k, l)=(-2A,-2B,-2C) \tag{4.2}$$

$$\text{Radius}(r)=h2+k2+l2-D \tag{4.3}$$

Through this interactive experience, trainees gain a deep understanding from a CMM stylus capturing data points to calculating dimensions of the spherical object. Additionally, they learn how to interpret X, Y, and Z coordinates to ascertain the diameter and radius of the stylus ball, which is critical in the dimensioning process. By the conclusion of this step, trainees are expected to proficiently calibrate and utilize the stylus in virtual CMM operation tasks for the precise dimensional analysis.



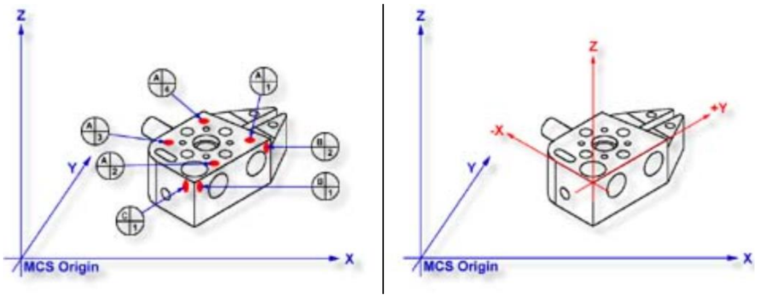


Figure 10: Stylus qualification process. **Figure 11**: PCS selection (a) Red dots for contacted points (b) PCS origin formed by red lines.

4.3 Coordinate System Selection

Following the stylus configuration, the next step in CMM training is the selection of coordinate systems. It defines a reference frame for accurate data interpretation and reporting. Trainees are introduced to the concept of the Machine Coordinate System (MCS) and Part Coordinate System (PCS) for positioning and measurement tasks.

The MCS is defined at the top right front of the machine and represents a fixed reference frame from the machine's perspective. To select this coordinate system in the training module, the user is required to perform a simple action by pressing a designated key. This one-step activation simplifies the process for beginners, allowing them to focus on the fundamentals of measurement.

In contrast, establishing PCS requires a more involved procedure, mirroring the complexity of real CMM operations. PCS is defined based on the workpiece's own geometry and can be located at any point of a workpiece. For educational purposes, the virtual training system prompts users to select PCS by tapping specified datum targets on the workpiece surface. The user must tap the stylus four times on the top plane, twice on the front plane, and once on the left plane. This is akin to touching these faces with the stylus to record X, Y, and Z coordinates at key points that are then used to determine the location of the PCS origin, as illustrated in Figure 11.

To mathematically derive coordinates at a point on the workpiece as the PCS origin (0,0,0). By tapping four points on the top plane, such as P1, P2, P3, and P4, the plane normal vector can be decided based on the plane equation:

$$Ax+By+Cz+D=0 \tag{4.4}$$

Two taps on the front plane, along with one point from the top plane, data points are collected to determine other vertical planes. The intersection of these planes is used to determine a corner point of the workpiece as the origin (0,0,0) of PCS. The trainees execute this sequence in the virtual environment, with each tap providing immediate visual and numerical feedback on the coordinate values obtained. The system processes the input data to decide the PCS origin, displaying the result for trainee understanding of the PCS process.

4.4 Dimension Measurement

In the subsequent step of the VR training, trainees perform the dimensional analysis on a variety of geometric features of the measured part, or workpiece. This phase of the training engages trainees in selecting the type of dimensions required, such as a point, line, circle, plane, sphere, cylinder, ellipse or cone. Each selection prompts the user to engage in a series of virtual measurements using x, y, and z coordinates that are then used to calculate the desired dimensions. The user interface for the measurement is shown in Figure 12. The dimensional analysis procedures are as follows.

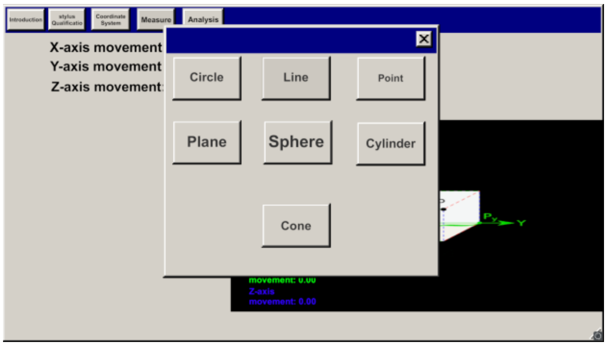


Figure 12: Features to be dimensioned in CMM.

4.4.1 Point Measurement

Process: A single tap is performed on the workpiece to capture x, y, z coordinates of a point.
Formula: The coordinates are recorded as a vector P= (x, y, z).

4.4.2 Line Measurement

Process: Two points on the workpiece are tapped to define a line segment.
Formula: The distance between two points, P1 and P2, is decided using the distance formula:

$$d=(x2-x1)^2+(y2-y1)^2+(z2-z1)^2 \qquad (4.5)$$

Vector Form: The line vector representation is found by subtracting coordinates:

$$L=P2-P1 \qquad (4.6)$$

4.4.3 Circle Measurement

Process: Three taps on the workpiece define a circle's boundary.
Formula: The circle in a 3D space is determined using the coordinates of three non-collinear points, P1, P2, and P3.
Radius and Diameter: Once the circle's plane and center are calculated, the radius is the distance from the center to any of the three points, and the diameter is twice the radius.

4.4.4 Plane Measurement:

Process: Two taps on each plane define the corners of a rectangular section of the plane.
Formula: The equation of a plane using three points P1, P2, P3 is: $n\cdot(r-r0)=0$, where n is the normal vector to the plane, and r0 is the position vector of an arbitrary point P1 on the plane.
Parallel Distance: The distance to another plane parallel to the first is computed by substituting the coordinates of a point on the second plane into the first plane equation.

For example, the height of a workpiece is measured and compared to its true value of the design as shown in Figures 13 and 14.

Figure 13: Height measurement.

Figure 14: True value in the design.

4.4.5 Sphere Measurement:

Process: A series of points are tapped around the sphere's surface to determine its center and radius. Formula: The sphere equation is derived from the coordinates of measured points, like the circle, but in three dimensions to account for the additional degree of freedom.

4.4.6 Cylinder Measurement:

Process: Points are measured along the top and base circles and along the cylinder height.
Formula: The diameter and height of the cylinder are calculated by finding the dimensions of the bounding circles and the distance between them.

4.4.7 Cone Measurement:

Process: Points on the base circle and cone side are measured to establish the slant height and base radius.
Formula: The base radius is calculated for a circle, and the slant height is calculated using the Pythagorean theorem from the apex to any point on the base circle.

During this dimensional measurement step, trainees interact with a 3D model of the workpiece in the virtual environment. They perform virtual taps, much like real CMM measuring a physical object. The measured data are processed using the formulas provided, offering trainees an immediate and accurate calculation of the dimensions. This hands-on approach to learning concepts in dimensioning and performing precise measurements.

4.5 The System Evaluation

The system evaluation is considered for two purposes: assessing the training system and analyzing the user performance. The feedback in the form of questionnaires and surveys from the students, industry professionals, and professors who have experience using machine and VR-based training will be used to critically evaluate our training system for insights on the system's effectiveness in simulating real CMM operations and highlight areas where improvements can be made.

The system evaluation also involves a detailed analysis of trainee performance during the training sessions. It utilizes data collected during dimensioning exercises to provide comprehensive feedback on trainee measurement performance. This involves assessing results against set tolerance requirements and conducting statistical analysis to help users understand the variability and potential sources of any errors in the measurements. The CMM and workpiece in our lab allow us to make direct comparisons between virtual and actual measurements. To facilitate this, an automatic comparison feature is introduced, comparing the users' measurements in the virtual environment with true dimensions from the CAD model. This feature enables users to identify discrepancies and potential errors in their measuring techniques easily.

This evaluative process is crucial as it not only provides feedback on the trainee’s performance but also reinforces the necessary skills for accurate measurement. It is designed to highlight both strengths and areas needing more practice, ensuring that the virtual training experience effectively translates to practical skills in the real world. With this thorough evaluation, we are confident that trainees will develop a solid understanding of CMM operations and be well-prepared for the challenges of actual CMM tasks, thus enhancing the overall learning experience.

5 CONCLUSIONS

In conclusion, the development and implementation of the VR-based training system for CMM operations represent a significant advancement in the domain of precision measurement training. By integrating a comprehensive and interactive curriculum in the virtual environment, the system successfully demonstrates the ability to enhance learning outcomes through engaging and practical simulations.

The introduced system lays a strong foundation for trainees, equipping them with the knowledge and skills necessary to operate CMM with the high accuracy and efficiency. Our method facilitates a deep understanding of the complex interplay between theoretical principles and practical applications in measurement tasks. Furthermore, the interactive dimensioning exercises and feedback mechanisms serve as a solid platform for users to refine their measurement techniques in a controlled virtual environment.

For the future work, the scope of this research presents several exciting avenues for expansion and refinement. The transition towards an augmented reality (AR) system using devices such as HoloLens 2 will offer a more tangible interaction with training models, bridging the gap between virtual and physical realms. The integration of haptic devices and sensors for the collision detection is anticipated to further enrich the realism of the simulations, allowing users to gain tactile feedback and enhanced spatial awareness.

The practical applicability of the training system will be rigorously evaluated through extensive user studies to further validate its effectiveness. The comparison of data collected within the virtual environment against actual measurement data will provide invaluable insights into the system precision and reliability. Additionally, the implementation of a multi-user training system will cater to collaborative learning scenarios and enable tracking of individual training steps, fostering a competitive yet cooperative educational experience.

Ultimately, the continuous improvement and adaptation of this training system will aim to set a new standard in CMMs training, offering a sophisticated, cost-effective, and scalable solution that aligns with the technological advancements and evolving needs of manufacturing industry.

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REFERENCES

[1] Anagnostakis, D.; Ritchie, J.; Lim, T.; Sung, R.; Dewar, R.; ASME: A Virtual CMM Inspection Tool for Capturing Planning Strategies, ASME International Design Engineering Technical Conferences/Computers and Information in Engineering Conference (IDETC/CIE 2017), 2017, Aug 06-09, Cleveland, OH. https://doi.org/10.1115/DETC2017-67519

[2] Chen, Y.H.; Wang, Y.Z.; Yang, Z.Y.: Towards a haptic virtual coordinate measuring machine, International Journal of Machine Tools & Manufacture, 44 (10), 2004, 1009-1017. https://doi.org/10.1016/j.ijmachtools.2004.03.005

[3] Fang, F.; Li, Z.; Arokiama, A.; Gorman, T.: Closed Loop PMI Driven Dimensional Quality Lifecycle Management Approach for Smart Manufacturing System, 9th International Conference on Digital Enterprise Technology - Intelligent Manufacturing in the Knowledge Economy Era, 56, 2016, 614-619. https://doi.org/10.1016/j.procir.2016.10.121

[4] Feddoul, Y.; et al.: Exploring human-machine collaboration in industry: a systematic literature review of digital twin and robotics interfaced with extended reality technologies, International Journal of Advanced Manufacturing Technology, 129 (5-6), 2023, 1917-1932. https://doi.org/10.1007/s00170-023-12291-3

[5] Feng, X.; Zhang, J.; Du, C.; Li, X.; Xu, C.: Three-coordinate measuring machine probe pre-stroke error predicting method, 2017, Univ Anhui Technology Patent No. CN107480377-A and CN107480377-B.

[6] Franco, P.; Jodar, J.: Theoretical Analysis of Measuring Accuracy of Three Linear Axis CMMs from Position Errors, International Journal of Precision Engineering and Manufacturing, 21, 2020, 2235-2247. https://doi.org/10.1007/s12541-019-00198-7

[7] Gao, G.; Zhang, H.; San, H.; Wu, X.; Wang, W.: Modeling and Error Compensation of Robotic Articulated Arm Coordinate Measuring Machines Using BP Neural Network, Complexity, 2017. https://doi.org/10.1155/2017/5156264

[8] Gaska, A.; Harmatys, W.; Gaska, P.; et al.: Virtual CMM-based model for uncertainty estimation of coordinate measurements performed in industrial conditions, Measurement, 98, 2017, 361-371. https://doi.org/10.1016/j.measurement.2016.12.027

[9] Gaska, A.; Harmatys, W.; Gaska, P.; Gruza, M.; Sladek, J.: Validation of Virtual CMM-Based Method for Uncertainty Estimation of Measurements Performed on Five-Axis Coordinate Measuring Machines, 12th International Conference on Measurement and Quality Control - Cyber Physical Issue (IMEKO TC), 2019, Jun 04-07, Belgrade, SERBIA, 39-46. https://doi.org/10.1007/978-3-030-18177-2_4

[10] Geng, R.; Li, M.; Hu, Z; Han, Z.; Zheng, R.: Digital Twin in smart manufacturing: remote control and virtual machining using VR and AR technologies, Structural and Multidisciplinary Optimization, 65, 2022, 14. https://doi.org/10.1007/s00158-022-03426-3

[11] Keferstein, C.; Marxer, M.; Jakubiec, W.; Weckenmann, A.; Beetz, S.; VDI/VDE: EUKOM - European Training for Coordinate Metrology, 8th International Symposium on Measurement and Quality Control in Production, 2004, Oct 12-15, Erlangen, GERMANY, 351-358.

[12] Knoke, B.; Thoben, K. D.: Training simulators for manufacturing processes: Literature review and systematisation of applicability factors, Computer Applications in Engineering Education, 29, 2021, 1191-1207. https://doi.org/10.1002/cae.22378

[13] Kueng, A.; Meli, F.; Nicolet, A.; Thalmann, R.: Application of a virtual coordinate measuring machine for measurement uncertainty estimation of aspherical lens parameters, Measurement Science and Technology, 25, 2014. https://doi.org/10.1088/0957-0233/25/9/094011

[14] Kunzmann, H.; Trapet, E.; Waldele, F.: Coordinate Measuring Machines in the Calibration Chain, Ptb-Mitteilungen, 104, 1994, 348-356.

[15] Li, D.; Wang, Y.; Wang, R.; Jiang, B.: Towards an Internet-Based Virtual Coordinate Measuring Machine, International Conference on Intelligent Computation and Industrial Application (ICIA2011), 2011, Jun 18-19, Hong Kong, 485-488.

[16] Lin, Z.; Liu, Q.: Selection of coordinate measuring machines by the neural network method, International Journal of Advanced Manufacturing Technology, 13, 1997, 42-55. https://doi.org/10.1007/BF01179229

[17] Liu, X.; Ma, S.; Wu, P.; Chen, Z.: An Internet-based measurement system for coordinate measurement machines, Proceedings of the Second International Symposium on Instrumentation Science and Technology, Vol 1, 2002, 684-687.

[18] Lu, J.; Xu, G.; Fan, W.; Chen, Y.; He, G.: Training device body based three-coordinate measuring machine, 2017, Xinchang Ding Rui Technology Co Ltd Patent No. CN209328262-U.

[19] Luthuli, Z.; Schreve, K.; Kruger, O. A.: Towards a Virtual Optical Coordinate Measurement Machine, 8th International Conference on Competitive Manufacturing (COMA), 2023, Mar 09-10, 737-748. https://doi.org/10.1007/978-3-031-15602-1_53

[20] Marjanovic, M. A.; Stojadinovic, S. M.; Zivanovic, S. T.: Modelling and Simulating the Digital Measuring Twin Based on CMM, Modelling, 4, 2023, 382-393.

https://doi.org/10.3390/modelling4030022

[21] Neamtu, C.; et al.: Training in coordinate measurement using 3D virtual instruments, Measurement, 45 (10), 2012, 2346-2358. https://doi.org/10.1016/j.measurement.2011.09.026

[22] Orrego, R.; Di Giacomo, B.; Sato, D.; Aspe, A.: A reduced synthetization model for virtual CMM, Proceedings of the Thirteenth Annual Meeting of the American Society for Precision Engineering, 1998, 554-557.

[23] Pahk, H. J.; Burdekin, M.; Peggs, G. N.: Development of virtual coordinate measuring machines incorporating probe errors, Proceedings of the Institution of Mechanical Engineers Part B-Journal of Engineering Manufacture, 212, 1998, 533-548. https://doi.org/10.1243/0954405981515833

[24] Peng, Q.; Zhao, L.: Development of a CMM training system in virtual environments, Proceedings of the ASME International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, DETC 2010, 6, 537-544. https://doi.org/10.1115/detc2010-28274

[25] Sang, Y.; Sun, W.; Wang, X.: Research on the development of an interactive three coordinate measuring machine simulation platform, Computer Applications in Engineering Education, 26 (5), 2018, 1173-1185. https://doi.org/10.1002/cae.21970

[26] Santos, J. E.; Nunes, M.; Pires, M.; Rocha, J.; Sousa, N.; Adao, T.: Generic XR game-based approach for industrial training, International Conference on Graphics and Interaction (ICGI), Nov 03-04, 2022. https://doi.org/10.1109/ICGI57174.2022.9990346

[27] Stojadinovic, S.; Zivanovic, S.; Slavkovic, N.: Verification of the CMM Measuring Path Based on the Modified Hammersly's Algorithm, 12th International Conference on Measurement and Quality Control - Cyber Physical Issue (IMEKO TC), 2019, Jun 04-07, Unv Belgrade, Fac Mech Engn, Belgrade, SERBIA, 25-38. https://doi.org/10.1007/978-3-030-18177-2_3

[28] Unity Real-Time Development Platform, 3D, 2D, VR & AR Engine, https://unity.com/, Unity.

[29] Wang, Y.; Chen, Y.; Accessibility analysis for CMM inspection planning using haptic device, IEEE International Conference on Robotics and Biomimetics, 2006, Dec 17-20, 1239. https://doi.org/10.1109/ROBIO.2006.340105

[30] Wang, Y.; Zhang, W.; Chen, Y.; Liu, D.; Zhang, R.; Accessibility Analysis for CMM Inspection Planning by Means of Haptic Device and STL Representation, IEEE International Conference on Virtual Environments, Human-Computer Interfaces and Measurement Systems, 2009, May 11-13, Hong Kong, 174. https://doi.org/10.1109/VECIMS.2009.5068888

[31] Zhang, Y.; Nee, A.; Fuh, J.; Neo, K.; Loy, H.: A neural network approach to determining optimal inspection sampling size for CMM, Computer Integrated Manufacturing Systems, 9, 1996, 161-169. https://doi.org/10.1016/S0951-5240(96)00005-5

[32] Zhao, L.: Development of a VR-based CMM System for Industry Training and CMM Path Planning, Dissertation, Thesis, 2013, University of Manitoba.

[33] Zivanovic, S.; Stojadinovic, S.; Marjanovic, M. A.: Modelling and Simulating the Digital Measuring Twin Based on CMM, Modelling, 4, 2023, 382-393. https://doi.org/10.3390/modelling4030022.