Practice Paper

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ENHANCING INDUSTRIAL TRAINING: DEVELOPMENT OF A VR GRINDING SIMULATOR FOR MANUFACTURING EDUCATION

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ABSTRACT

This article presents the development and pedagogical and technical foundations of a virtual reality (VR) grinding simulator designed for industrial training. The simulator is part of the Manufacturing Academy 2.0 project, a collaboration between Tampere University of Applied Sciences and SASKY education association, which aims to address skill shortages in the manufacturing industry by providing immersive and scalable training solutions. The simulator enables trainees to engage in realistic and interactive learning scenarios that replicate the grinding workflow in industrial settings, without the safety risks and material costs associated with traditional hands-on training. Rather than simulating the physical mechanics of grinding, the simulator focuses on modelling the full grinding process, including workpiece setup, parameter selection, validation measurements and safe machine operation. Developed iteratively through collaboration with machine shops, industry professionals, and educators, the simulator incorporates authentic grinding machine models and real workpieces. It also features pedagogical enhancements such as a built-in “Master Button” which functions as a built-in expert assistant, mirroring the ability to asking for guidance from a senior colleague.

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1 INTRODUCTION

Industry 4.0 represents a shift toward smart, interconnected, and data-driven manufacturing. It enhances productivity, efficiency, and flexibility while also posing challenges related to cybersecurity, investment costs, and workforce adaptation (Pereira & Romero, 2017). Virtual reality (VR) technologies are increasingly being adopted in industrial training as part of the digital transformation associated with Industry 4.0. These technologies provide immersive and interactive learning experiences that can simulate complex manufacturing processes with a high degree of realism (Paszkiewicz et al., 2021). In this context, VR simulators are used to train employees in various industrial applications, ranging from machining and welding to assembly and maintenance. VR-based training methods have demonstrated significant improvements in training efficiency, cost reduction, and safety outcomes compared to traditional methods (Firu et al., 2021).

“Manufacturing Academy 2.0” is a project implemented jointly by Tampere University of Applied Sciences and SASKY education association. It aims to promote skills and training in key manufacturing processes relevant to the manufacturing industry in Finland in order to both respond to the labour shortage and implementation of the goals of the green and digital transition. The project will implement a training pilot, during which a group of learners will be trained to respond to the growing and immediate labour demand of one of the manufacturing industry’s processes, grinding. The “Manufacturing Academy 2.0” project has developed a VR simulator as a training tool, designed to improve skill acquisition in grinding processes while reducing the risks and costs associated with traditional training methods. It also enables initial training without the need for real, physical griding equipment.

2 PEDAGOGICAL ASPECTS OF VIRTUAL REALITY SIMULATORS IN INDUSTRIAL TRAINING

From a pedagogical perspective, VR training offers several advantages over traditional instructional methods. Research indicates that VR-based learning enhances engagement, retention, and skill acquisition due to its immersive nature (Paszkiewicz et al., 2021). The ability to interact with a simulated environment provides trainees with real-time feedback, allowing them to refine their techniques and develop a deeper understanding of the processes involved. Furthermore, VR training can be adapted to different skill levels, providing customized learning experiences tailored to individual needs. VR-based training environments enable learners to engage in realistic, interactive simulations that closely resemble real-world industrial settings, thereby facilitating hands-on skill development in a controlled and risk-free manner (Asad et al., 2021). This aligns with experiential learning theories, which emphasize active participation and reflection as critical components of skill acquisition. Studies indicate that VR-based learning promotes deeper understanding through active exploration, immediate feedback, and multi-sensory interaction, surpassing text-based methods in effectiveness (Hamilton et al., 2021). Furthermore, VR supports constructivist learning approaches by allowing trainees to practice tasks repeatedly until proficiency is achieved, which is particularly beneficial in complex manufacturing processes (Agbo et al. 2023). Additionally, VR enables customized learning experiences, accommodating diverse skill levels and learning paces, thus optimizing the training process (Bernardo & Duarte, 2022).

One significant concern in using VR is the potential for cognitive overload due to the high level of immersion and the complexity of virtual environments (Agbo et al., 2023). Additionally, motion sickness and fatigue have been reported among some users, potentially hindering learning outcomes (Hamilton et al., 2021). Moreover, the high initial investment required for VR infrastructure, including hardware, software development, and integration with existing training programs, poses a financial barrier for many institutions (Bernardo & Duarte, 2022). Another critical consideration is the need for pedagogically sound instructional design to ensure that VR-based learning experiences align with industry competencies and training objectives (Asad et al. 2021).

One of the primary benefits of VR-based industrial training is the ability to offer a safe and controlled learning environment. Traditional training for complex industrial tasks, such as grinding, often involves exposure to hazardous conditions, including high-speed rotating machinery, flying debris, and intense heat. By using VR, trainees can practice essential skills in a virtual setting before transitioning to real-world operations, reducing the risk of workplace injuries (Chandra Sekaran et al., 2021). Additionally, VR simulators enable repetitive practice without the consumption of physical materials, thereby minimizing waste and optimizing resource utilization. This is particularly relevant in industries where raw materials and components are costly, making VR a more sustainable and cost-effective training solution (Paszkiewicz et al., 2021).

3 DEVELOPMENT OF THE GRINDING SIMULATOR

To ensure the simulator accurately reflects industry practices, production managers and grinding professionals from machine shops were interviewed during different development phases. Their insights helped refine the training content, user interface, and operational logic of the simulator. These discussions provided input on grinding parameters, workpiece handling, and process safety, helping to ensure that the simulator prepares trainees for real-world tasks. The simulator has been designed not to simulate the physical interactions of grinding at a microscopic level; instead, the VR simulator models the operational steps and decision-making processes involved in an actual manufacturing grinding workflow.

Additionally, a manufacturer of grinding equipment provided a 3D model of an actual grinding machine, Studer S40 CNC (Fig. 1 A). This allowed the development team to create a highly realistic virtual environment. To further enhance authenticity, actual workpieces, axles (Fig 1 C), from industrial production were obtained, along with their technical drawings, enabling the simulator to incorporate realistic geometries and tolerances. During the grinding workflow, the operator needs to check that the dimensions are in accordance with the drawings. Therefore, also virtual measurement tools are modelled for intermediate and final inspection measurements. Micrometre and dial indicator are shown in Fig. 1 B and C. All these assets were important in making the simulation environment visually and functionally accurate, reinforcing its role as an effective educational tool.

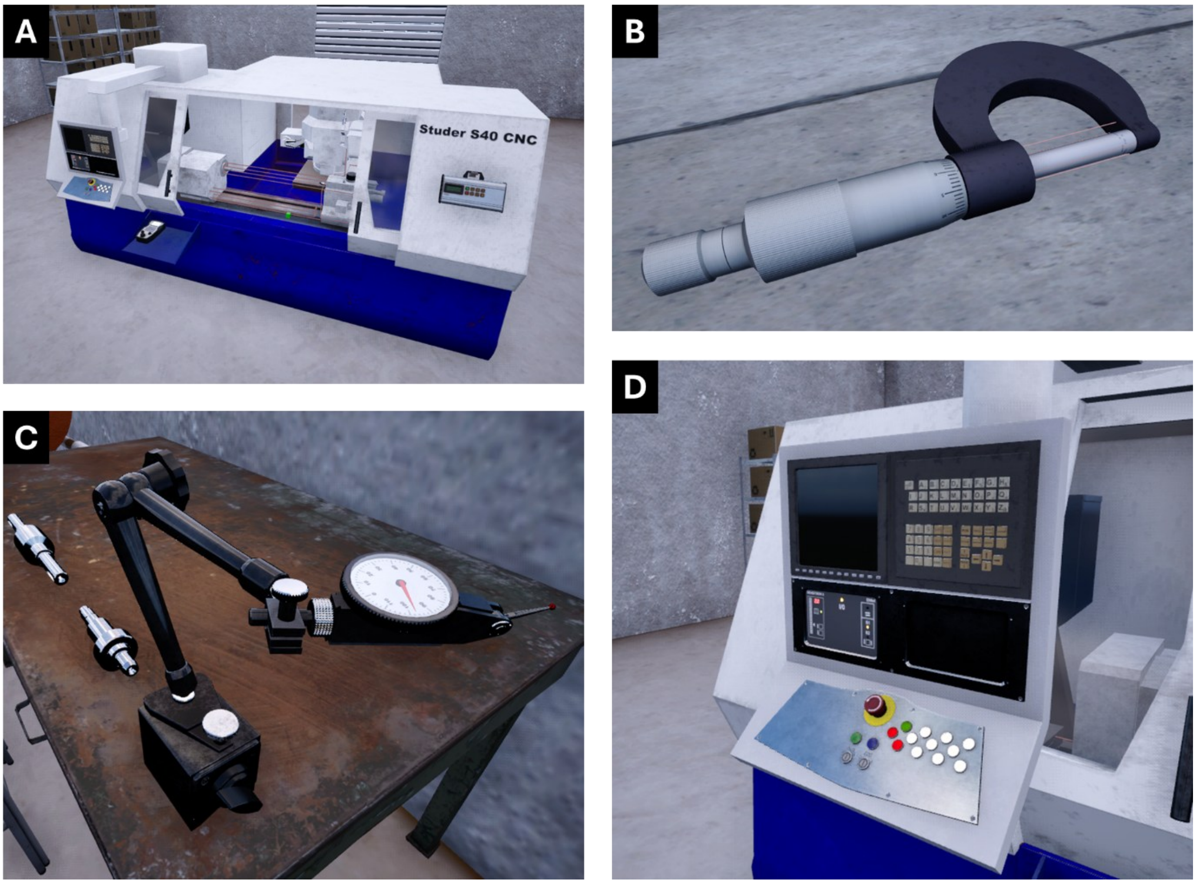

Fig.1. Virtual 3D model of the Studer S40 CNC grinding machine (A), Virtual 3D models of precision measurement tools included in the grinding simulator, micrometre (B) and dial indicator (C) are used for intermediate and final inspection measurements as part of the grinding workflow. In (C) also virtual models of axels are shown. Virtual model of the control panel of the grinding machine. The interface includes typical industrial elements such as a display, keypad, emergency stop button, and operational controls (D).

A conceptual flow chart (Fig. 2) was created early in the simulator development process to support shared understanding among team members and industry experts. This diagram mapped out the key components and operational sequence of the grinding simulator, helping to clarify what the simulator is designed to do and how users are expected to interact with it. The chart was developed iteratively based on project experiences and grinding operator feedback. Its purpose was not only to guide development but also to ensure that the simulation process aligns closely with the actual workflow in industrial grinding environments.

The development effort has required approximately 1.5 person-years of coding and implementation work, distributed among two coding instructors and two student developers. In addition, background research and collection of tacit knowledge were carried out by other project staff. While it is difficult to separate the portion specifically supporting the VR simulator, it certainly amounts to several person-months of work.

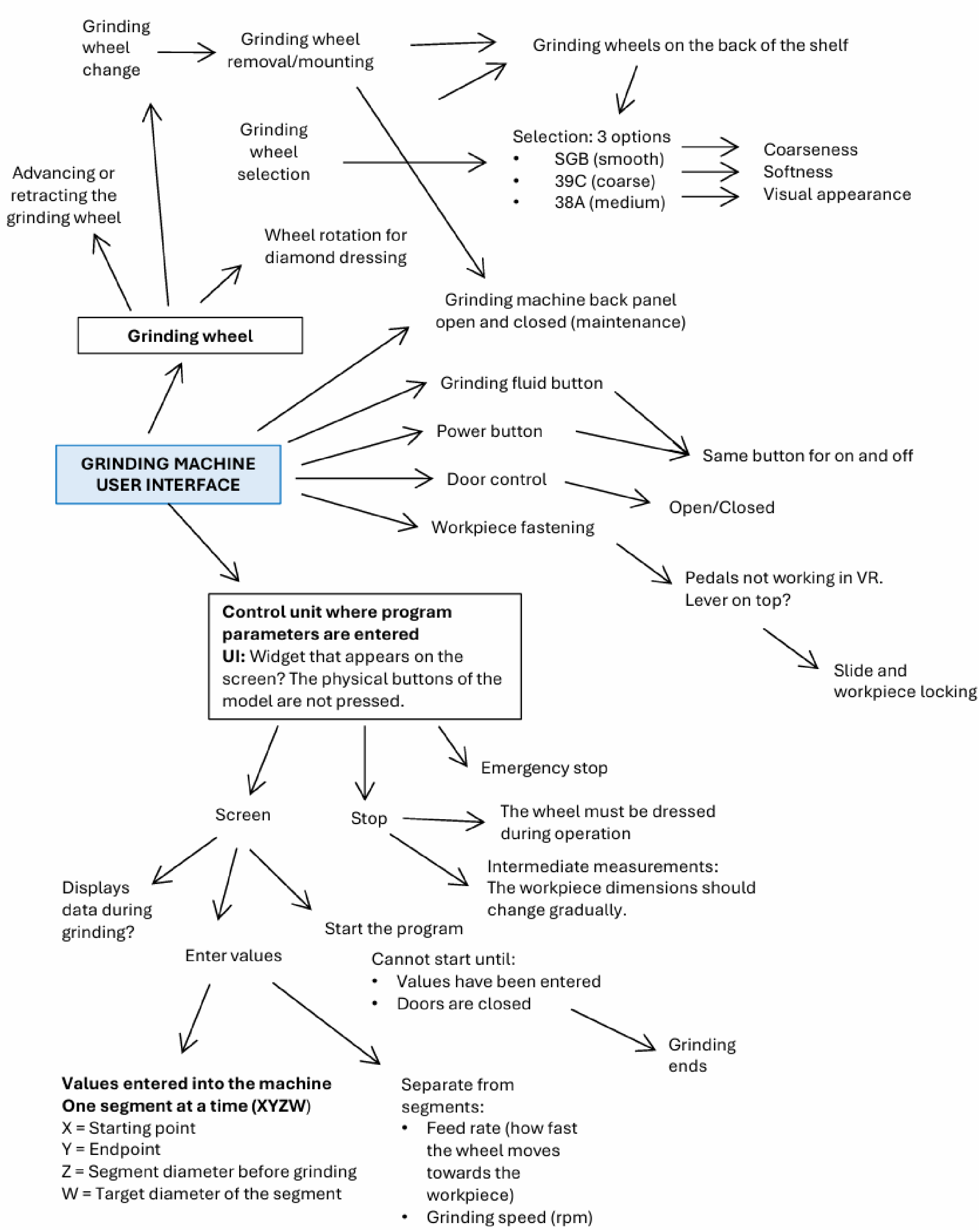

Fig. 2. A conceptual flow chart mapping out the key components and operational sequence of the grinding simulator.

3.1 Technical implementation

Several implementation options were explored early in the simulator development, including Virtual Reality (VR), Augmented Reality (AR), a browser application, and a native 3D application. The browser and native applications were ruled out due to limited immersion and accessibility challenges, and AR was dismissed as it required access to a real grinding machine, reducing simulator versatility.

VR was ultimately chosen for its immersive environment and independence from physical equipment. Modern headsets like Meta Quest 3 enable standalone use, making the solution portable and user-friendly. Development was built on a game engine, with Godot excluded due to instability and lack of VR development experience. Unity, though familiar to the team, was unsuitable due to its subscription-based licensing. Unreal Engine was selected for its high-quality graphics and academic licensing model. Its Blueprint visual scripting system provided an accessible development path despite the team's limited C++ experience.

Unreal Engine also offered strong compatibility with VR hardware and development toolkits, making it a future-proof choice for simulation-based training. Its capacity for realistic rendering supported the project's goal of creating an authentic learning environment that closely mimics real-world grinding workflows.

The final technical setup targets the Meta Quest 3 headset, chosen for its balance of affordability, standalone performance, and ease of deployment. Its wireless nature eliminates the need for external computers, making the simulator portable and practical for use in diverse training environments. While other VR devices can be supported, each requires custom integration, especially regarding control schemes. Meta’s standardized platform simplifies development and maintenance, allowing the team to focus on refining learning content and user experience while maintaining flexibility for future expansion.

3.2 Grinding exercises

The simulator’s training structure is composed of a series of modular learning tasks, each representing a discrete step in the grinding process. These tasks were defined in collaboration with grinding professionals and educators, and they reflect the competencies required of workers operating grinding machines. The training progression begins with basic steps such as workpiece positioning and securing, followed by parameter input and grinding wheel selection, and culminates in process execution, intermediate measurements, and final evaluations together with proper documentation. Each learning task contributes to a larger, interconnected sequence that mirrors the complete grinding workflow. This design allows learners to gradually build their expertise through focused practice, while still understanding how each step fits into the broader process.

3.3 Industry Insights for the Development of the Grinding Simulator

A co-creation workshop for the Manufacturing Academy 2.0 project was arranged to gather insights from industry representatives regarding the development and optimization of the grinding simulator. The workshop participants, consisting of professionals from manufacturing companies, educators, and students, engaged in hands-on testing of the VR simulator (Fig. 3.), followed by structured discussions. Their feedback highlighted key areas for improvement, including usability, immersion, learning structure, and integration into training programs.

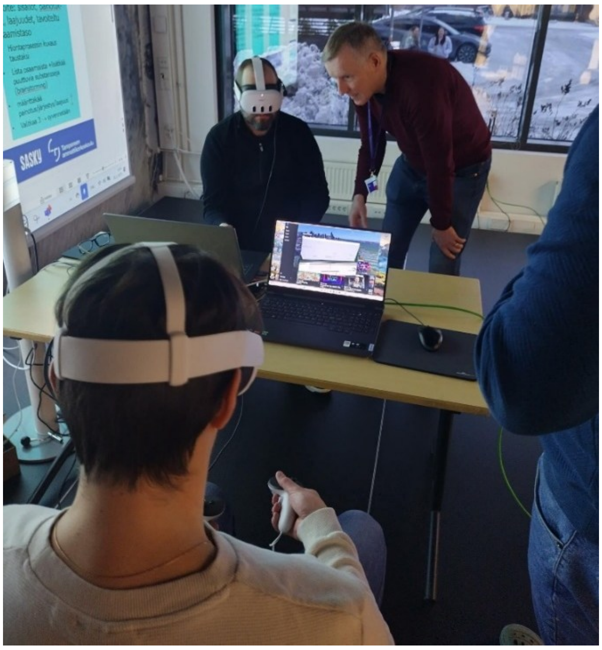

Fig. 3. testing the VR grinding simulator during a co-creation workshop. Participants used standalone VR headsets to explore the virtual environment while developers gathered feedback to refine usability and pedagogical features. (Photo: Riika Kankaanpää).

Industry representatives noted that younger learners found the simulator intuitive due to prior gaming experience, whereas others required additional training to familiarize themselves with the control panel and interface. A structured onboarding process was recommended to ensure a smooth learning curve, supported by real-time guidance from an instructor during initial exercises. The visual accuracy was deemed sufficient, participants suggested incorporating an audio environment to reflect real-world grinding sounds, as these auditory cues play a role in process monitoring. From a pedagogical perspective, the simulator should focus on experiential learning by implementing cause-and-effect scenarios where users learn through trial and error. Essential training modules identified by industry representatives included safety procedures, precision measurement, and machine maintenance. These elements would improve the simulator’s role in reinforcing fundamental grinding concepts.

Participants also stressed the educational value of the simulator, particularly for novice operators, as it allows for safe and cost-effective training. While the simulator was not even considered a full replacement for hands-on grinding practice, it was recognized as a valuable tool for understanding grinding principles and visualizing internal machine operations. The ability to repeat exercises without material waste was considered important. The immersive and game-like VR simulator can also serve as an effective tool for attracting young people to the industry, lowering the threshold for exploring careers in manufacturing.

To further support the learning process and replicate real-world workplace dynamics, a "Master Button" feature was invented in the co-creation workshop. In manufacturing environments, less experienced workers can seek assistance from a senior colleague or supervisor when they encounter difficulties. This informal peer learning process is important for developing expertise and problem-solving skills. To mirror this aspect in the virtual environment, the simulator's "Master Button" functions as a built-in expert assistant. When activated, it provides context-sensitive guidance, such as visual cues, step-by-step instructions, or best practice recommendations relevant to the trainee's current task. This ensures that users receive timely support without disrupting the training session, reinforcing independent learning while maintaining a structured support system. By integrating this feature, the simulator enhances self-directed learning and problem-solving while still preserving the collaborative nature of skill development found in industrial workplaces.

After the simulator has been piloted in training at companies, user feedback will be collected from both students and professional grinders to assess its usability and learning effectiveness. This feedback will guide further refinements to ensure the simulator meets the needs of real industrial training contexts.

4 CONCLUSIONS AND IMPLICATIONS

The development of the VR grinding simulator within the Manufacturing Academy 2.0 project demonstrates how immersive technologies can address the evolving training needs of modern manufacturing industries. The simulator offers a safe, and cost-effective supplement to traditional grinding instruction by enabling learners to engage in realistic, step-by-step training without requiring access to physical equipment. The focus was on modelling the entire grinding workflow rather than simulating material removal physics.

The iterative development process was guided by input from educators, machine shop professionals and students. It resulted in a simulator that combines technical realism with learner-centered instructional design with authentic 3D models, real-world workpieces, and measurement tools. Pedagogical aspects such as modular learning tasks and the "Master Button" feature support experiential and self-directed learning while mimicking workplace-based peer learning. Technically, the simulator is built using Unreal Engine and optimized for the Meta Quest 3 headset, offering a portable, high-performance solution suitable for varied educational environments.

Industry feedback has confirmed the simulator's usability, educational value, and potential to attract new talent into the field. The next step is to implement the simulator in selected pilot trainings, where its educational effectiveness and practical value will be further evaluated and developed in authentic training contexts. The simulator is intended for integration into both vocational and higher education programs, including TAMK and SASKY students, and offered to other educational institutions. Moreover, companies can use the simulator for in-house training purposes. Future work will focus on integrating the simulator into authentic educational contexts and refining its implementation in both vocational and higher education curricula.

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