3D Model-Based Safety Training System for Ship Auxiliary Machinery Assembly-Disassembly Experiments

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Abstract. Disassembly and assembly experiments of ship auxiliary machinery are vital practical courses for marine engineering students, involving operations on pumps, compressors, hydraulic systems, etc., which carry inherent risks such as mechanical injury and electric shock. Traditional safety education for these experiments often lacks specificity, interactivity, and a measurable assessment mechanism, resulting in limited student engagement and inadequate risk preparedness. To address these shortcomings, this project introduces a three-dimensional (3D) modelling and virtual simulation-based safety education and training system. High-precision 3D models of typical auxiliary equipment (e.g., pumps, valves, motors) are created, accompanied by operational and fault demonstration animations. Students can interactively perform virtual disassembly and reassembly, identify potential hazards, and experience the outcomes of incorrect operations in a risk-free environment. A structured assessment mechanism is implemented, requiring students to pass virtual safety evaluations before they can progress to practical training. This system aims to improve safety awareness, standardise operational procedures, and enhance risk identification and emergency response capabilities.

Keywords: 3D modeling; virtual simulation; safety education; ship auxiliary machinery; practical training

1 Introduction

Currently, integrating simulation technology into practical teaching is widespread and is fundamentally transforming the traditional engineering education model. Engineering education is increasingly focusing on utilizing modern technologies and tools to help students comprehend complex technical processes [1]. In the specific area of assembly and disassembly training, three-dimensional (3D) digital virtual simulation technology has been proven to effectively improve teaching quality and foster students' practical innovation skills by visualizing internal structures that are normally invisible [2]. Additionally, the use of Virtual Reality (VR) and gamification in engineering courses has been shown to significantly increase student engagement, motivation, and retention of complex concepts compared to traditional approaches [3].

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In the field of marine engineering, particularly for ship auxiliary machinery, traditional training methods often fall short due to high operational risks and the complexity of equipment. For example, disassembling and assembling hydraulic equipment are key practical skills, yet students frequently lack opportunities for dynamic characteristic analysis and performance testing in static learning settings [4]. To fill these gaps, researchers have explored various virtual solutions. Winther et al. showed through a case study on pump maintenance that VR training can effectively teach sequences of tasks, providing a safe environment for trial and error that complements hands-on training [5]. Similarly, developing ship virtual trial training platforms has become urgent to support multi-domain ship testing and comprehensive effectiveness evaluation, overcoming resource coordination limitations in physical trials [6].

Technologically, building these systems depends on robust modeling and analysis tools. SolidWorks is widely used in designing valves and mechanical components to create accurate 3D models and check for interference [7]. Beyond geometric modeling, ensuring the structural integrity and safety of virtual equipment is crucial. Wang et al. used Failure Mode and Effect Analysis (FMEA) combined with ANSYS structural strength analysis for hydraulic jacking systems, providing a theoretical basis for simulating failure modes in training scenarios [8]. Advancing practical training, the concept of Digital Twins (DT) is transforming education. Cao et al. proposed a teaching model based on digital twins that maps intelligent manufacturing production lines into virtual space, creating a "virtual-real symbiosis" that addresses high risk and costs associated with physical experiments [9]. Looking ahead, the comprehensive framework of virtual-real integration in unmanned systems indicates a trend where virtual environments will not only be used for training but also interact dynamically with physical systems to boost autonomy and decision-making [10].

Building on these foundations, this project presents a 3D model-based safety education and training system. By combining high-precision modeling, fault simulation, and a structured assessment mechanism, the system seeks to bridge the gap between theoretical knowledge and practical risk management.

2 Instructional Programme

To address the limitations of traditional comprehensive training for ship auxiliary machinery, such as limited teaching scenarios, high operational risks, and students' abstract understanding, this research develops an integrated "virtual simulation first, hands-on verification afterward" teaching system. The core of this system involves using 3D modeling software to create highly detailed digital models of key auxiliary equipment. As shown in valve design applications, SolidWorks enables the creation of parameterized models that support quick modifications and assembly verification [7]. Figure 1 shows an exploded view of a disassembled gear pump, clearly illustrating the structure and spatial relationships of all internal parts. Figure 2 displays the complete 3D assembly model of the same gear pump.

Students can download these models from the database before class and, guided by the accompanying interactive practice manual and standard operational demonstration videos, independently complete the assembly and disassembly procedures of the equipment within a virtual environment. To enhance learning, the system pre-sets various typical fault conditions (e.g., part wear, assembly errors, seal failures) within the models. Our system allows students to construct simulation circuits and analyze dynamic characteristics, rather than just observing external appearances. Furthermore, to improve safety awareness, we incorporate failure mode analysis similar to the structural strength analysis performed on hydraulic systems [8], enabling students to visualize the consequences of critical failures such as component fracture or overload. This approach guides students to proactively identify, analyze, and optimize components during the virtual disassembly/assembly process, thereby integrating theoretical knowledge with troubleshooting skills.

To ensure the high fidelity required for engineering training, the parametric modeling approach in SolidWorks was utilized. The modeling process followed a strict "Part-Subassembly-General Assembly" workflow.

Sketching and Feature Construction: Based on the actual 2D engineering drawings of the centrifugal pump, the base features were created using operations such as Extrude, Revolve, and Sweep. For complex curved surfaces like the impeller blades, the Loft feature was applied to ensure aerodynamic accuracy.

Assembly Constraints: In the assembly environment, standard mates (e.g., Concentric, Coincident, and Parallel) were defined to restrict the Degrees of Freedom (DOF) of each component, simulating real-world mechanical constraints.

Interference Detection: Before exporting the models, the Interference Detection tool was employed to automatically identify overlapping geometries between the shaft and the bearings, ensuring zero-collision in the static state.

Rendering and Material Definition: Physical properties (e.g., steel, rubber) were assigned to each part to generate realistic textures and weights, which are crucial for the subsequent dynamic simulation.

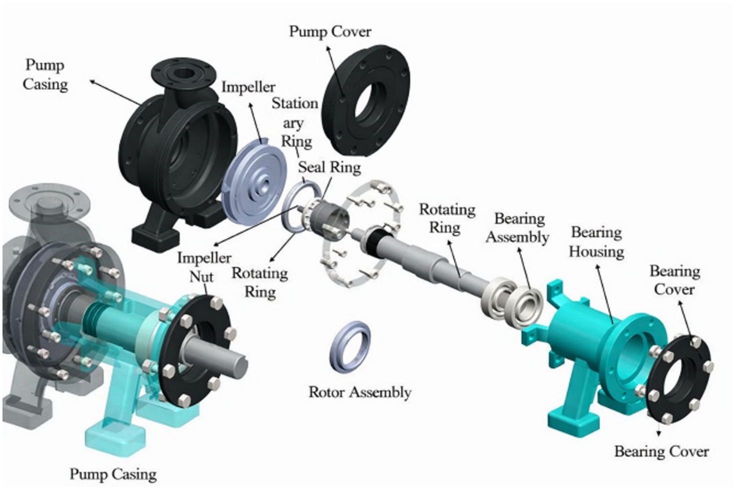

Fig. 1. 3D model of the centrifugal pump after disassembly.

The fault simulation mechanism is implemented through parameter perturbation and collision logic algorithms, specifically addressing two categories of faults: Dimensional Faults (e.g., Component Wear): We utilized the Equations Manager in SolidWorks to create configuration sets. For a "shaft wear" fault, the variable controlling the shaft diameter is linked to a global variable. In the fault mode, the system triggers a script to reduce by 0.5mm, visually representing the gap and affecting the virtual assembly fit. Assembly Logic Faults: The system integrates a real-time Collision Detection Algorithm. Virtual colliders are attached to key mating surfaces (e.g., the bolt and the nut thread). If a student attempts to install a component in the wrong sequence or orientation, the system detects the collider overlap, calculates the intersection volume, and immediately triggers a "Collision Warning" animation (highlighting the part in red) to simulate the inability to assemble, rather than just displaying a text prompt.

Fig. 2. 3D model of a centrifugal pump after assembly.

Fig. 3. Interference detection analysis in SolidWorks: The red volume indicates a dimensional conflict between the shaft and the bearing inner ring.

Specifically, the Interference Detection tool in the Evaluate module is employed to validate the assembly logic. As illustrated in Figure 3, when a student attempts to assemble components with mismatched dimensions (e.g., an oversized shaft), the system executes a Boolean intersection algorithm. The overlapping volume is rendered in red to serve as an immediate visual alarm, while the non-interfering geometries are rendered transparently. This visual feedback allows students to intuitively locate the precise position and magnitude of the assembly error. Such as Figure 3 and 4.

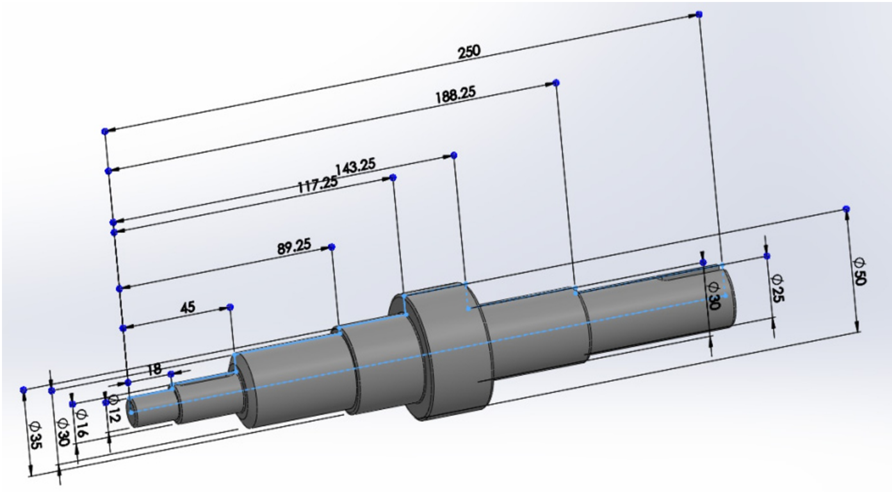

Fig. 4. Set the incorrect size.

After completing systematic virtual simulation training, students move on to the physical laboratory to perform hands-on disassembly and assembly of actual equipment. This progressive "virtual-first, hands-on-follow-up" training approach ensures both safety and operational efficiency during the practical phase. Based on a case study of gear pump maintenance, this training pathway can reduce on-site operational risks by 60%. The virtual training environment plays an important preparatory role: it not only vividly demonstrates potential injuries through imagery (as shown in Figure 5) to increase students' safety awareness before working with physical equipment, but instructors can also intentionally set common assembly errors in the 3D models, such as dimensional mismatches or incorrect component configurations (as shown in Figures 6). This allows students to learn how to identify, diagnose, and correct faults in the virtual environment, directly applying these skills in subsequent hands-on operations with equipment like centrifugal pumps. Experience indicates that this approach, through cross-verification between 3D simulations and physical equipment, significantly enhances students' proficiency with modern engineering design software and deepens their understanding of internal equipment structures, component connection methods, and power transmission concepts. Figure 7 depicts students conducting on-site disassembly and assembly of a centrifugal pump. Particularly during fault analysis and solution design stages, students are better able to identify root causes and understand cause-and-effect relationships in mechanical failures, thereby developing strong engineering practical skills and innovative thinking abilities.

Fig. 5. Schematic diagram of personnel injured during handling.

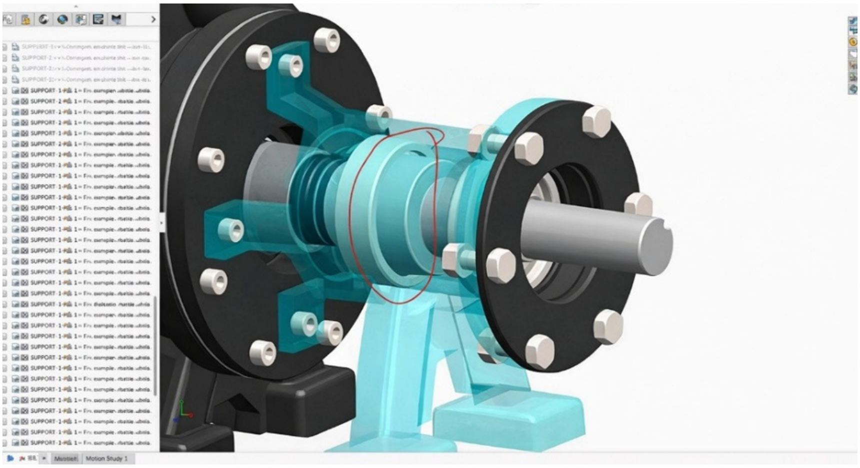

Fig. 6. The model is incorrectly configured.

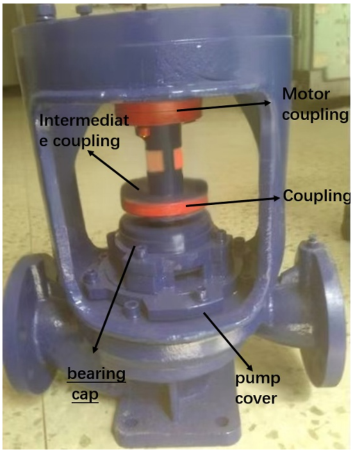

Fig. 7. Disassemble the centrifugal part pump.

3 Scheme Process

Based on the training objectives of the Comprehensive Auxiliary Machinery Training, which aim to develop students' overall practical skills in understanding the structural principles, standard operations, and fault diagnosis of complex auxiliary equipment, this course has created a systematic "Four-Stage Progressive" implementation plan.

3.1 Reform of Student-Centred Teaching Model: Backed by Virtual Simulation Research

First, Student-Centered Reform of the Teaching Model. This initiative fundamentally shifts the traditional teacher-led instruction model to a classroom focused on students' independent inquiry and collaborative learning. By incorporating virtual simulation cases, students can independently explore mechanism principles [11]. By setting exploratory tasks and organizing group analysis and solution discussions, it significantly enhances students' sense of involvement, initiative, and internal motivation throughout the entire training process.

3.2 Developing Engineering Skills through Varied Instruction with 3D Digital Models

Second, Integration of Diversified Teaching Methods. High-precision 3D digital models are thoroughly integrated into all stages of instruction. Students not only use the models for preview and observation but are also tasked with completing the modeling, modification, and assembly verification of specified components using 3D software. We have moved beyond simple checklists to a multi-dimensional evaluation system. Peng et al. proposed an integrated testability evaluation model based on Bayes' theory and multi-source data fusion for ship electrical equipment, which addresses the problem of low credibility in small-sample experiments [12]. This process turns abstract knowledge into tangible understanding, effectively fostering students' spatial imagination, structural design skills, and proficiency in modern engineering software, thereby significantly improving the effectiveness and depth of practical training.

3.3 Comprehensive Practical Skills Assessment through Integrated Practice-Assessment Reform

Third, an integrated design of practice and assessment mechanisms. Practical training adopts the approach of "Virtual Simulation First, Hands-On Verification Follows." Students must initially learn equipment disassembly and assembly procedures, as well as fault diagnosis methods, in a 3D virtual environment before operating physical equipment in the laboratory. The assessment system has been reformed accordingly, establishing a comprehensive evaluation that includes "3D Modelling Assignments, Virtual Simulation Operations, Hands-On Performance, and Fault Analysis Reports," with a focus on assessing students' practical skills and engineering thinking. Figures 4 and 5 display the incorrect size and model.

3.4 Quantitative Assessment and Teaching Effectiveness

Fourth, to ensure the quality of auxiliary machinery comprehensive training, a rigorous examination and evaluation system has been established. Following the standard workflow for auxiliary equipment design and maintenance, the final assessment is divided into five weighted modules: 3D component optimization (10%), virtual 3D model assembly and disassembly (30%), animation simulation (10%), physical on-site assembly and disassembly (30%), and fault analysis (20%). This reformed teaching system has been fully implemented across the Marine Engineering major at our university, involving a total of 275 undergraduates. Post-course practical assessments and survey data show substantial improvements in learning outcomes compared to traditional methods. Specifically, quantitative analysis indicates that over 65% of students demonstrated a significantly deeper understanding of the operational principles of centrifugal pumps and reported greater ease in handling the equipment. Additionally, approximately 50% of students achieved a high level of proficiency in SolidWorks modeling techniques, which effectively enhanced their learning efficiency and engineering design capabilities. The complete technical roadmap of this project is shown in Figure 8.

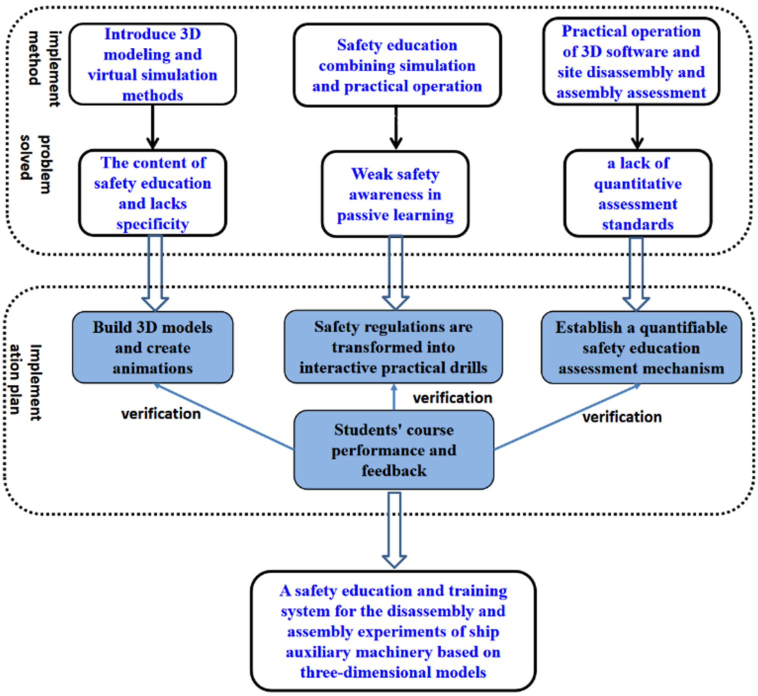

Fig. 8. Teaching framework diagram.

4 Conclusions

This project explores the creation and use of a 3D model-based safety education and training system for experiments involving ship auxiliary machinery. Using virtual simulation technology, it overcomes the limitations of traditional passive safety instruction. The system provides an immersive, interactive, and risk-free environment that helps students understand hazards, practice proper procedures, and see the consequences of mistakes, thereby enabling them to better internalize safety principles.

The integrated "theory-simulation-practice-assessment" approach ensures that safety education is targeted, engaging, and measurable. It allows students to move beyond simply following rules to actively practicing safety-conscious behaviors. This model not only improves the safety culture in laboratories but also helps develop future marine engineers with strong safety skills, innovative problem-solving abilities, and a deep sense of professional responsibility, establishing a solid foundation for their career development.

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