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Assessing the Usability of an Immersive Computer Assembly Simulation Based on Hand Gesture Control

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Abstract

Vocational computer assembly training frequently relies on conventional static media, which fails to provide the interactive spatial visualization necessary for mastering complex hardware handling. This study aims to develop and evaluate the usability and pedagogical effectiveness of a computer assembly simulation utilizing hand gesture control to address this educational gap. Employing the Research and Development (R&D) methodology guided by the ADDIE framework, the interactive medium was developed using Unity 3D and the Leap Motion Controller. Following rigorous validation by media and material experts, a field evaluation was conducted involving 30 vocational high school students. The System Usability Scale (SUS) was administered to assess user experience, while a pre-test and post-test design, analyzed via a Paired Sample T-Test, measured the impact on learning outcomes. Expert appraisals categorized the simulation as "Very Feasible," scoring 89.1% for media and 79.58% for material quality. The user evaluation yielded an average SUS score of 64.6 ("Marginal High"), reflecting a minor initial learning curve associated with the novel controller-free interface. Crucially, the intervention significantly enhanced student performance, with average scores increasing from 57.00 to 87.00 (Sig. = 0.000). These findings demonstrate that despite moderate initial cognitive friction regarding usability, immersive hand gesture simulations profoundly elevate practical skill mastery, offering a secure and highly effective pedagogical alternative to traditional didactic instruction.

1 Introduction

In the landscape of modern vocational education, particularly within Computer and Information Engineering (Teknik Komputer dan Informatika/ TKI) programs, computer assembly remains a fundamental competency that students must master. This subject emphasizes the technical synergy of integrating various hardware components into a functional personal computer system (Hardianto et al., 2024; Maryati et al., 2016). Ideally, the mastery of these skills requires instructional methods that involve active student participation and direct demonstration. Students are expected to understand complex component layouts and physical handling to ensure technical readiness before engaging with actual laboratory equipment. Mastering these skills is not merely about theoretical knowledge but involves high-precision motor coordination to avoid the high risk of hardware failure due to improper handling (Pieschacon et al., 2024). Traditional laboratory settings, while effective for developing hands-on proficiency, frequently impose substantial logistical burdens on vocational programs, such as constraints on individualized practice opportunities arising from equipment scarcity, where multiple students often share limited resources, along with challenges related to limited physical space, safety risks from handling delicate components, and the need for intensive supervision to prevent hardware damage.

However, the current reality in vocational training reveals a significant gap between pedagogical ideals and classroom practice (Badarudin et al., 2024). Educational media often rely on conventional modules, static presentations, and non-interactive videos. These traditional tools are frequently criticized for their lack of visualization and inability to provide a realistic simulation of the assembly process. For instance, students at the vocational level often encounter difficulties in conceptualizing the spatial placement of components when only exposed to two-dimensional media. Consequently, this limitation leads to a lack of engagement and may increase the risk of damaging sensitive electronic parts during actual physical practice, primarily because two-dimensional representations fail to convey the intricate spatial relationships and tactile nuances essential for precise component handling, causing students to misinterpret layouts, commit assembly errors, and experience frustration that exacerbates disengagement and elevates hardware damage risks during initial hands-on attempts (Criollo-C et al., 2024; Sırakaya & Çakmak, 2018). These deficiencies highlight an urgent need for innovative instructional technologies that can bridge the chasm between theoretical comprehension and practical application, thereby enhancing academic achievement and cultivating confidence in vocational students.

To bridge this gap, the integration of immersive technologies, specifically hand gesture-based simulations, offers a promising solution. Unlike conventional mouse and keyboard interfaces that often distance the user from the digital environment, hand gesture control allows for more natural and intuitive interactions (Kaushik, 2024). Facilitated by devices such as the *Leap Motion Controller*, this technology can track 3D finger and hand data at high speeds, enabling users to "*grasp*" and "*manipulate*" virtual objects in a way that mimics real-world movements. Previous research suggests that immersive hand gesture systems can enhance the sense of realism compared to traditional input methods (Chakravarthi et al., 2023; Joshi, 2024). This technological leap transforms the assembly simulation into an immersive environment where students can focus entirely on the spatial tasks without being hindered by complex keyboard commands. This direct manipulation capability fosters a more profound understanding of the intricate procedures involved in computer hardware assembly, thereby overcoming the limitations of traditional didactic approaches (Checa et al., 2021; Olade, 2025). This approach directly addresses the challenges of limited laboratory resources and the inability of static media to convey procedural complexity

Despite the sophistication of immersive technologies, their educational effectiveness is heavily dependent on their usability. Usability is a critical determinant of whether a newly developed learning medium will be successfully adopted in a classroom setting (Alexandre et al., 2018; Bailey et al., 2022). In a virtual computer assembly simulator, measuring the user experience is essential to ensure that the precision of hand-tracking aligns with user expectations and physical comfort. If the interaction is perceived as cumbersome or counter-intuitive, the cognitive load required to operate the system may overshadow the actual learning material (Jamalian et al., 2022; Mulders et al., 2020). Thus, evaluating the system's usability through rigorous scientific frameworks, such as the System Usability Scale (SUS), is imperative to validate the system's readiness for educational integration. This evaluation should encompass not only the technological usability but also the pedagogical and sociocultural aspects to ensure comprehensive integration into the learning ecosystem (Singh & Ahmad, 2024).

This study aims to assess the usability of an immersive computer assembly simulation based on hand gesture control developed using the ADDIE (Analysis, Design, Development, Implementation, and Evaluation) framework. The novelty of this research lies in its specific focus on evaluating a controller-free interaction model for vocational hardware training, which remains an underexplored area in interactive learning media. By utilizing the SUS, this research provides a quantitative and qualitative analysis of how vocational students interact with the immersive environment. The findings are expected to offer significant contributions to the development of highly usable and acceptable immersive simulators that can mitigate the risks of physical practice while maintaining a high level of interactive realism.

2 Methodology

2.1 Research Design

This study utilized the Research and Development (R&D) method, which is defined as a research approach used to produce specific products and test their overall effectiveness (Vuletic et al., 2019). The selection of this method is justified by its capacity to facilitate a longitudinal and phased development process, starting from an initial needs analysis to empirical testing in a real-world educational environment. For instance, this approach is highly appropriate for developing a hand gesture-based simulation as it allows the researcher to systematically bridge the gap between conventional teacher-centered learning and immersive, technology-driven instruction. By employing R&D, the study ensures that the resulting interactive medium is not only technically functional but also significantly contributes to improving student learning outcomes in complex subjects like computer assembly. Ultimately, this methodology provides a framework for validating the product's feasibility through expert appraisal and user feedback before final implementation (Checa et al., 2021).

The development process specifically followed the ADDIE model, which consists of five systematic phases: Analysis, Design, Development, Implementation, and Evaluation (Hidayatullah et al., 2024). This model was chosen because its structured and iterative workflow ensures that both the technical and pedagogical requirements for a hand gesture-based simulation are meticulously addressed. Furthermore, the ADDIE framework provides a rigorous foundation for developing high-quality educational software by allowing continuous refinement through its systematic stages, which is essential for ensuring the product's overall effectiveness. By utilizing this phased approach, the study can systematically bridge the gap between conventional teaching methods and immersive, technology-driven instruction. Ultimately, this model supports a longitudinal development process that facilitates rigorous validation through expert appraisal and user feedback. The detailed flow of activities for each phase is presented in Figure 1.

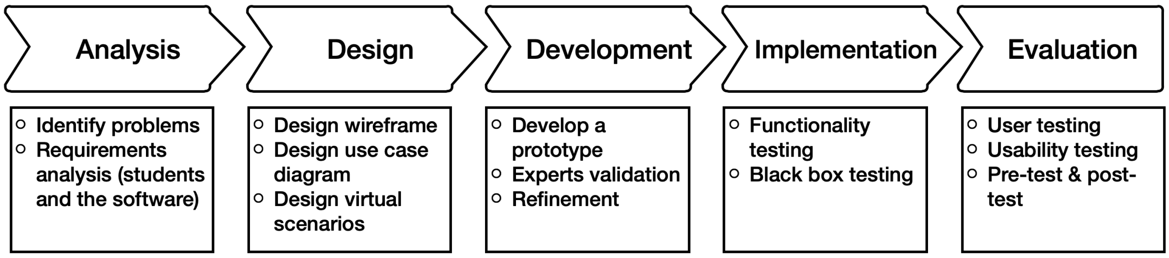

Figure 1. Detail activities each phase

The *Analysis* phase focused on identifying existing learning problems in the classroom, where it was found that teachers primarily utilized conventional media such as modules, textbooks, PowerPoint, and videos. This stage also involved identifying the students' need for more interactive and immersive media to facilitate their understanding of complex computer hardware components and layouts. Additionally, a comprehensive requirements analysis was conducted to determine the necessary software, specifically *Unity engine*, and the hardware required for hand motion capture, namely *the Leap Motion Controller*. These identified needs served as the fundamental basis for the subsequent development stages.

During the *Design* phase, the system's architecture was planned to meet the identified needs, starting with the creation of a Use Case Diagram to represent the interactions between the user and the simulation system. The structural layout and interaction flow of the simulation, including the main menu, component introduction, virtual practice rooms, and assembly challenges, were further detailed through wireframes. Following this, the *Development* phase involved the actual construction of the interactive medium using Unity 3D for the simulation environment and visual assets development. Initial validation was then performed by media and material experts to ensure the product's technical and pedagogical feasibility, followed by revisions based on their feedback.

In the *Implementation* phase, the developed system was technically tested using the Black Box method to ensure that all functional requirements, such as precise hand motion capture and collision detection, operated as planned. Finally, the Evaluation phase involved user testing involving 30 students from class X of a vocational school. During this stage, the system's usability was measured using the SUS to determine user acceptance. Additionally, the simulation's effectiveness was assessed through a comparison of pre-test and post-test results to determine its impact on student learning outcomes.

2.2 Participants and Setting

The participants in this study consisted of 30 students from the Class X Computer and Network Engineering (TKJ) program at a vocational high school. This specific group was selected because computer assembly is a mandatory foundational subject for tenth-grade students within the Computer and Informatics Engineering expertise program. The setting for the research was the school's computer laboratory, providing a relevant environment for testing an immersive learning tool. Participants were chosen to evaluate the usability and effectiveness of the hand gesture-based simulation in a real-world educational context where traditional media like PowerPoint and video are typically used. To ensure ethical standards and participant privacy, school identity details are kept confidential, focusing instead on the demographic and technical background of the users. Detailed demographic characteristics of the participants are presented in Table 1.

Table 1. Demographic profile of the participants

Demographic Variable	Category	Frequency (n)	Percentage (%)
Gender	Male	17	56.70%
	Female	13	43.30%
Age	15 years old	20	66.60%
	16 years old	10	33.30%
Prior Experience with Similar Apps	Yes	5	16.70%
	No	25	83.30%
Duration of Use	Never	25	83.30%
	< 1 month	5	16.70%
Total participant		30	100%

2.3 Data Collection and Analysis Techniques

Data collection was conducted using a mixed-methods approach to ensure a thorough evaluation of the hand gesture-based simulation. Expert validation involved the administration of structured questionnaires to both media and material experts, assessing critical aspects such as instructional design, visual communication, and software functionality. To measure the user experience from a technical perspective, the SUS was employed, featuring 10 standardized items to gauge student satisfaction and perceived ease of use. Furthermore, the educational impact of the simulation was quantified by comparing results from pre-tests and post-tests, which participants completed before and after interacting with the medium.

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The technical analysis of the product's feasibility utilized percentage formulas to transform quantitative expert scores into qualitative categories, ranging from "Less Feasible" to "Very Feasible". To ensure the statistical validity of the assessment instruments, Aiken's V formula was applied to calculate the content validity coefficient for each item. Additionally, the internal consistency and reliability of these research tools were verified using Cronbach's Alpha, ensuring that the collected data remained consistent across multiple administrations. User satisfaction was further evaluated through specific questionnaires, enabling the collection of qualitative feedback on the interaction and overall learning experience (Yamtinah et al., 2023).

Usability data from the SUS questionnaires were analyzed following specific scoring rules, where individual scores were calculated and multiplied by 2.5 to determine the final average score and its corresponding grade scale. This allowed for the categorization of the system's usability into adjective ratings such as "Excellent" or "Acceptable". Finally, to determine the simulation's effectiveness on learning outcomes, a Paired Sample T-Test was performed at a 0.05 significance level. This statistical test was used to identify significant differences between pre-test and post-test scores, thereby justifying the simulation's impact on student performance compared to conventional methods. This comprehensive methodological framework allowed for a robust assessment of the simulation's pedagogical efficacy and its practical utility as an educational tool (Naser, 2024; Yamtinah et al., 2023).

3 Results and Discussion

3.1 Application Features and Expert Judgement

The primary outcome of this research is an immersive computer assembly simulation medium that utilizes hand gesture control technology via the Leap Motion Controller. This application is designed to transform the learning experience from conventional teacher-centered methods, which often rely on static media like PowerPoint and video, into an interactive 3D environment. Within this simulation, students can perform virtual practices such as recognizing hardware components and demonstrating the assembly process through natural hand movements. The system effectively bridges the gap between theoretical knowledge and practical application by providing a risk-free environment for students to familiarize themselves with complex hardware layouts. Ultimately, this technology-driven medium aims to foster a more engaging and immersive classroom atmosphere that supports modern vocational education requirements. academic benefit for the students.

The application features several key modules, including component introduction, 3D animated video tutorials, virtual assembly practice, and assembly challenges. In the "Simulation" scene, as shown in Figure 2, users are presented with a 3D workspace containing a computer casing and various interactive hardware buttons. This environment allows students to virtually pick up and place components, such as the motherboard, processor, and power supply, into the casing using precise hand gestures detected by the sensor. These features are directly aligned with the learning outcomes of the Class X TKJ curriculum, which requires students to demonstrate proficiency in disassembling and assembling computer components. By providing real-time audio guidance and visual feedback, the simulation ensures that students can achieve measurable mastery of the subject matter in an interactive setting.

The development process successfully integrated functional interactivity, allowing users to manipulate 3D objects as if they were in a physical laboratory. For instance, the "Challenge" module includes a scoring system to evaluate students' memory and understanding of component placement, with each correct action awarding points. This gamified approach not only increases student motivation but also provides a measuring tool for teachers to assess learning progress measured against the established passing criteria (KKM). The immersive nature of the hand gesture interface provides a sense of realism that is unattainable through traditional mouse-and-keyboard interactions. Consequently, the simulation serves as a comprehensive educational tool that meets both technical and pedagogical standards for vocational high school training.

Figure 2. Simulation scene of computer assembly

Before the user testing phase, the simulation underwent rigorous evaluation by two media experts and three material experts to ensure overall quality and feasibility. The results from the media expert validation indicated a high feasibility rating, with a total average percentage of 89.1%, placing the product in the "Very Feasible" category. This assessment covered crucial aspects such as instructional design, visual communication, and software functionality. Furthermore, statistical analysis using Aiken's V yielded a coefficient of 0.88, while the reliability test using Cronbach's Alpha resulted in a score of 0.811. These scores confirm that the media assessment instruments were both valid and demonstrated strong reliability.

The material expert validation also produced positive results, with an average feasibility score of 79.58%, which also falls into the "Very Feasible" category. The material experts, consisting of experienced vocational teachers, evaluated the simulation's alignment with the current curriculum and the depth of the educational content. Statistical validation for the material instruments showed an Aiken's V average of 0.73 and a Cronbach's Alpha reliability of 0.750, indicating strong internal consistency. Additionally, technical functionality was verified through Black Box testing, which achieved a 100% success rate across all 40 tested items, including sensor detection and collision responses. Based on these expert findings, the simulation was deemed technically sound and pedagogically appropriate for field implementation.

3.2 User Evaluation

To evaluate the hand gesture-based learning medium for computer assembly, a user experiment was conducted involving 30 students. The usability of the verified simulation was assessed using the SUS questionnaire, a standardized instrument consisting of ten items designed to provide a reliable assessment of perceived ease of use and student satisfaction. The raw scores collected from the participants were processed using standard SUS calculations, where odd-numbered items are subtracted by 1 and even-numbered items are subtracted from 5, with the total sum then multiplied by 2.5. This evaluation provides a comprehensive understanding of how students interact with the Leap Motion-based interface in a practical vocational setting. Detailed itemized results of the SUS assessment, including the average adjusted and normalized scores for each questionnaire item, are presented in Table 2.

The analysis of the questionnaire data revealed that the simulation achieved an average SUS score of 64.6. According to the SUS interpretative framework, this score is categorized as "Marginal High" in terms of acceptability. Furthermore, it corresponds to a "Good" adjective rating and a Grade Scale of "D". While these results indicate that the medium is generally functional, the "Marginal High" status highlights that students, who are primarily accustomed to conventional modules and books, may find the non-touch hand gesture interaction initially challenging. This score serves as a critical baseline for further refining the application's interaction design to achieve a higher level of user mastery and comfort.

Table 2. Summary of SUS score

Questions No.	RAW	Adjusted Score (0-4)	Normalized Score (0-100)
1	3.63	2.63	65.8
2	2.43	2.57	64.2
3	3.93	2.93	73.3
4	3.47	1.53	38.3
5	4	3	75
6	3.93	2.7	67.5
7	2.2	2.93	73.3
8	2.2	2.8	70
9	4.13	3.13	78.3
10	3.4	1.6	40
		2.58	64.6

Beyond the usability assessment, the study evaluated the simulation's effectiveness in improving student learning outcomes through a pre-test and post-test design. Students initially completed a pre-test consisting of 10 multiple-choice questions to establish their baseline knowledge of computer components and assembly before using the simulation. Following interaction with the immersive practice and challenge modules, a post-test of similar complexity was administered to measure cognitive gains. This comparative approach allowed for a direct quantification of how immersive, motion-controlled technology impacts the mastery of practical vocational skills compared to traditional static media.

The statistical evaluation of the assessment data demonstrated a substantial improvement in student performance. The average score increased from 57.00 in the pre-test to 87.00 in the post-test, representing a significant learning gain of 35%. Further analysis using a Paired Sample T-Test yielded a significance value (Sig. 2-tailed) of 0.000, which is well below the 0.05 threshold for statistical significance. These results confirm that the hand gesture-based simulation is effective in helping students master computer assembly and has a meaningful influence on their learning outcomes. The comprehensive comparison of learning results is summarized in Table 3.

Table 3. Comparison of student learning outcomes (pre-test vs. post-test)

Measurement	Mean Score	N	Std. Deviation	Sig. (2-tailed)
Pre-test	57.00	30	21.36	0.000
Post-test	87.00	30	11.19	

3.3 Discussion

The development of the immersive computer assembly simulation successfully addresses the pedagogical gap in vocational training by shifting away from conventional, static instructional media. Built upon the structured ADDIE framework, the resulting application offers a 3D environment where students can manipulate virtual hardware using natural hand gestures, effectively bridging the gap between theoretical knowledge and practical application without the risk of damaging physical components. The foundational quality of this technological intervention was strongly supported by expert evaluations prior to user testing. Both media and material experts categorized the simulation as "Very Feasible," awarding it scores of 89.1% and 79.58%, respectively, which confirms that the tool is technically robust and tightly aligned with the current vocational curriculum.

When deployed in a real-world classroom setting, user testing provided nuanced insights into the system's practical usability. The SUS evaluation yielded an average score of 64.6, placing the simulation in the ”Marginal High” acceptability range, which corresponds to a ”Good” adjective rating. While this indicates that the learning medium is functionally viable, the ”Marginal High” status suggests that students, who are heavily accustomed to traditional books and modules, experienced an initial learning curve when adapting to a non-touch, controller-free interface. This usability metric highlights that while the technology is promising, introducing highly immersive hand gesture controls into traditional classrooms requires an adjustment period for users to achieve complete operational comfort.

Crucially, despite the moderate usability score, the hand gesture-based simulation demonstrated a profound and positive impact on student learning outcomes. The empirical data revealed a substantial cognitive improvement, with average scores increasing significantly from 57.00 in the pre-test to 87.00 in the post-test. This 35% gain in learning achievement was proven statistically significant through a Paired Sample T-Test, which yielded a significance value of 0.000. These findings strongly suggest that the ability to physically simulate the assembly of components in a gamified, immersive space enhances spatial understanding and memory retention far better than static, two-dimensional educational media.

Ultimately, the integration of hand gesture control within a virtual assembly simulator serves as a highly effective, modern educational intervention for vocational high school students. The simulation successfully mitigates the risks and limitations of physical laboratory practice while fostering a highly engaging classroom atmosphere. Moving forward, while the pedagogical effectiveness of the tool is unequivocally validated by the significant learning gains, future iterations of the software should focus on refining the interaction design. Addressing the initial user friction reflected in the SUS score will help elevate the usability, ensuring that students can fully immerse themselves in the learning material without any cognitive load diverted to mastering the controls.

4 Conclusion

In conclusion, the implementation of a controller-free, hand gesture-based immersive simulation proves to be a transformative pedagogical strategy for vocational hardware training. By providing a risk-free, highly interactive 3D environment, the system successfully bridges the gap between theoretical comprehension and practical motor skill execution. Although the novelty of the non-touch interface introduces a moderate initial learning curve for students accustomed to traditional media, its educational impact is profound. The simulation significantly elevates student mastery of complex computer assembly procedures, demonstrating that immersive spatial learning tools can effectively surpass conventional static media in fostering critical technical competencies.

Despite these promising results, this study is subject to several limitations. The research was conducted with a constrained sample size of 30 students within a single vocational setting, focusing exclusively on one foundational competency, which may limit the broader generalizability of the findings. Future research is recommended to involve larger, more diverse participant demographics, expand the immersive simulation to encompass other complex vocational subjects, and conduct longitudinal evaluations to assess long-term practical skill retention.

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