Development of Simulation-Based Learning: G-code Programming for CNC Milling in Vocational Colleges

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Received: 16 August 2024
Received in revised form: 2 December 2024
Accepted: 15 December 2024
Published: 24 December 2024

ABSTRACT

Traditional teaching approaches for g-code programming of CNC milling machines can be difficult for students to visualise the machine movements related to g-code. g-code programming for CNC milling is one of challenging concepts, requires an in-depth understanding and experience with the movement of the cutting tool. Simulation-based learning is an innovative teaching and learning method that can help students comprehend g-code CNC milling machines. The DDR model is used in the development of g-code simulation of a CNC milling machine and consists of three main phases such as requirement analysis, design and development and evaluation. The simulation was design and develop using Articulate Storyline 360. The benefit using Articulate Storyline 360 it is ability to integrate several interactive media into single application. Feedback from expert and students indicates that simulation content aligns with vocational college syllabus. It is also stated that the simulation easily to understand and use. Overall, these finding suggest that simulation-based learning can enhance students' understanding by allowing them to visualize g-code programming for CNC milling machine.

Keywords (Times New Roman, bold, 9)
Simulation-Based Learning; g-code CNC Milling; DDR model.

Introduction

Industrial Machining title is quite significant at the vocational school. It is one of the specialized subjects aimed at providing students with the knowledge and skills to create, manage, and supervise the systems and tools preowned in the cutting-edge technology. The course provides up-to-date job training that is in line with the rapidly advancing technology for different contexts (Nasseer & Hasan, 2020). This not only develop students' technical skills, also prepare them for the future of workforce in the industrial sector.

To develop parts from design to product with acceptable accuracy, compatibility, machinability, and processability on a Computer Numerical Control (CNC) machine tool, certain steps must be followed. Krcheva et. al., (2023), CNC is the method of controlling machine tools automatically using a microcontroller and program control unit. g-code, which is a calculation formula using points, circles, and lines to create movement, is implemented in the CNC machines, which allows for the precise control of the tool movement for the operations like milling, plotting, and scratching (Abd Rahman et. al., 2023; Basheer, 2020). Even if it is a crucial part, the g-code language has it is own limitations definitions of various functionalities are not implemented in the g-code language, which is characterized by the difficulty in predicting commands and positions of the moving device with reference to the cutter (Yakovlev et. al., 2020).

An important aspect in developing programming is the need for skilled programmers and appropriate programming media (Arathaya et. al. 2011). Manufacturing training for the new employees is usually long as well as expensive because it consumes a lot of resources and is hazardous for the employees (Chryssolouris, 2013). When you add to this the real machinery training it can be even more expensive and disastrous in terms of resource consumption. Simulated training environments can also help to minimize these risky effects as well as bring up the cost (Daskalogrigorakis et. al., 2021). The trainees have difficulty understanding g-code programming on the machine's operations may lead to making a mistake.

The problems coming up in the current training methods is the unsuccessful traditional training on actual CNC machines demanding substantial financial investment and straining educational resources. The operational costs, such as machine maintenance and material costs, are the interesting factors that stand in the way of educational institutions providing the required hands-on training for all students. The exposure to actual CNC machines brings a certain degree of danger, especially for trainees who are new to the field (Lyu et. al., 2022). The possibility of accidents and injuries is a major concern that, in turn, demands the creation of secure spaces where students can acquire skills without the threat of harm. This is helping to avoid mistakes and ensure the product meets the specified specifications (Petrakov et.al., 2022). There is limited research on simulation-based learning as the tools for teaching vocational studies. In particular, the applicability of these tests to the improvement of students' mastering of the g-code operations procedure for CNC milling machines needs further investigation.

Simulation-Based Learning in CNC Machining

Simulation-based learning provides approximation of practice, overcoming limitations of real-life learning situations and can be effective in training complex skills (Chernikova et. al., 2020). In manufacturing simulation is a wide variety of computer-based applications emulating the behaviour of manufacturing systems (Radhakrishnan, et. al., 2008). Lo et. al. (2012), using simulation may allow students having understood well their functions properties and limitations. Complexities that come with planning before making things can be overcome using simulations as reference materials (Krcheva et. al., 2023). It's also allowing visual experience to learners in operation and g-codes CNC mill machines.

The use of simulation is important in explaining complex terms or problems. Simulation can help to explain by visualizing the movement of the cutting tool based on the g-code of the CNC milling machine. Simulation provides a clear picture of how the cutting process will be carried out and almost all aspects of machining can be shown, such as tool position, tool blade path, cutting operations and so on (Arathaya et. al., 2011). Simulation that describes in real-time the movement of the tool cutters can improve their understanding of the relationship between codes and machining operations (Praveen et. al., 2018). This not only improves student comprehension, but also reduces the risk of errors during practice, making the learning process more efficient and safer.

In conclusion, simulation-based learning offers a powerful and effective approach to teaching g-code programming for CNC milling. It addresses many of the limitations of traditional teaching methods by providing a safe, cost-effective, and scalable learning environment. However, to fully realize it is potential, simulation-based learning must be integrated thoughtfully with real-world practice and supported by high-quality, realistic simulation tools. As this technology continues to evolve, it is likely to become an integral part of vocational education, equipping students with the skills they need to succeed in modern manufacturing environments. Future research should focus on refining these tools, exploring their impact on learning outcomes, and developing best practices for their implementation in educational curricula.

Methods

This study uses the Design and Development Research (DDR) model to develop a simulation for g-code CNC milling machine. Using DDR in development is for guided the structured development and ensuring that each phase is thoroughly planned, executed and evaluated to produce a quality educational tool (Punithavili et. al., 2022). There are three main phases in DDR model are represented in Table 1.

Table 1. DDR model Phase

Phase of reseacrh	Evaluation technique
Phase 1: Needs Analysis	Literature Review and Interview
Phase 2: Design and Development	Simulation Development Using Articulate Storyline 360

	(Expert reviews)
Phase 3: Functionality	Quantitative Methods (Questionnaire)

Phase 1: Need analysis.

In the first phase, a need analysis was conducted to identify the specific g-code content for CNC milling machine taught at Vocational Colleges and to understand the difficulties students faced by students. To gather this information, three machining instructors from Vocational Colleges were interviewed using a semi-structured questionnaire. The feedback from the lecturers may helped the content requirement.

Phase 2: Design and development

The second phase focuses on the design and development of the simulation. The simulation was designed to ensure it aligns and relevant content for g-code CNC milling machine. This design phase includes three aspects: interface design, content design and interaction design. It is to ensure the development of simulation has user-friendly and relevance. Once the design was finalized, the simulation was developed using Articulate Storyline 360.

Phase 3: Functionality

The last phase of DDR model is functionality. This assessment was conducted to get feedback from three experts in multimedia and content. In other hands, 30 respondents from second years DVM students in industrial machining who had previously learn about the g-code CNC milling machine topics. The instrument used for functionality assessment was using 5-point Likert scale questionnaire, in aspects such as functionality simulation content and student understanding simulation operation. The data was analyzed using descriptive statistics, specifically percentage value.

Data Analysis and Results

In the initial phase of this study, a needs analysis was conducted to identify the primary challenges students face when learning g-code programming for CNC milling in Vocational Colleges. Based on interviews with three instructors specializing in industrial machining, a thematic analysis was performed to highlight the core issues affecting student comprehension.

A prominent theme that emerged from the interviews was the difficulty students experience in visualizing g-code movements during theoretical lessons. Both R1 and R3 emphasized that students often struggle to imagine the movement of the cutting tool when the explanation is provided verbally or through static illustrations in the classroom. As R1 noted,

…. Students find it challenging to perceive the actual movements taking place within the machine, especially when described only in theoretical terms without dynamic visual aids.

This difficulty in visualizing machine operations hinders students' ability to fully understand the concepts being taught. Another theme highlighted by R2 is the abstract nature of g-code itself, which further complicates the learning process. According to R2, students frequently encounter challenges in comprehending G-code commands, as these represent machine movements in coded instructions without any concrete visual representation. R2 explained,

…. It’s quite challenging for students to grasp something as abstract as g-code without visual aids that can show the actual movements.

This feedback underscores the need for instructional materials that can transform the abstract concept of g-code into visual forms that students can easily understand. These insights reveal a strong need for an interactive simulation that can help students visualize CNC machine movements in real-time, thereby enhancing their understanding of g-code programming. Both themes point to the potential effectiveness of a dynamic learning tool that bridges the gap between theoretical coding and tangible machine operations.

Design and Development Simulation

The second phase is design and development simulation design. This phase involves planning the structure and functionality of the simulation application, including the user interface (UI) (**Figure 1**), content interface (**Figure 2 (a)** and **(b**) and simulation application's interaction design **(Figure 3**). This design also includes aspects of visualizing g-code movements in CNC milling machines.

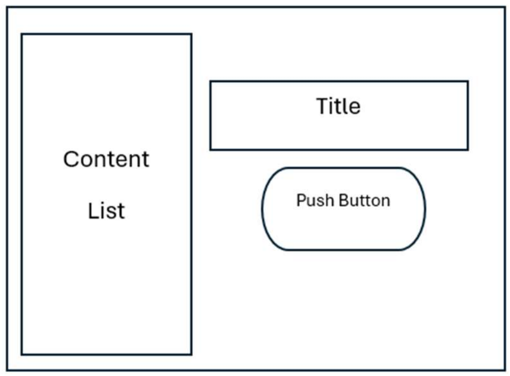
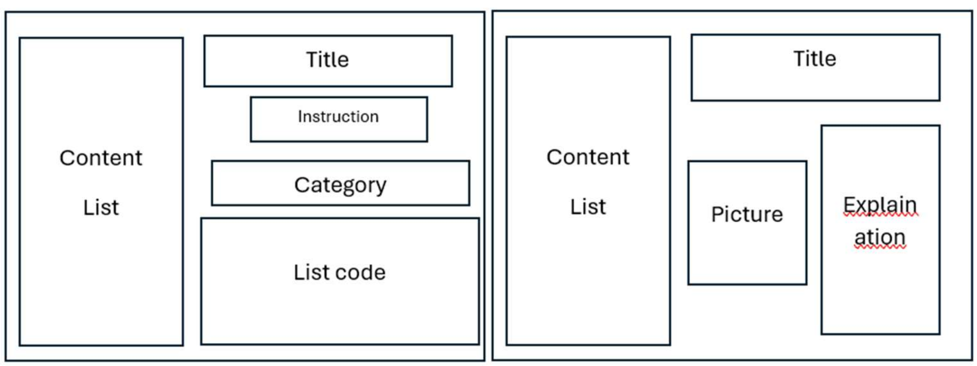


Figure 2. User interface (UI)



(a) (b)

Figure 3. Content interface

Figure 2 presents the UI design for the CNC milling machine simulation application. The interface is divided into several main sections facilitating navigation and user interaction, which include introduction, List of g-codes and simulation. In this introductory part, a general description of the program and it is major functionalities are provided. It helps the user understand how to use it properly. Figure 3(a) and (b) shows the CNC milling machine simulation content interface. The content interface includes a list of g-codes and simulation section. The user can select the g-code that they want to study by clicking the list code button. After that, the simulation interface promptly displays the g-code simulation.

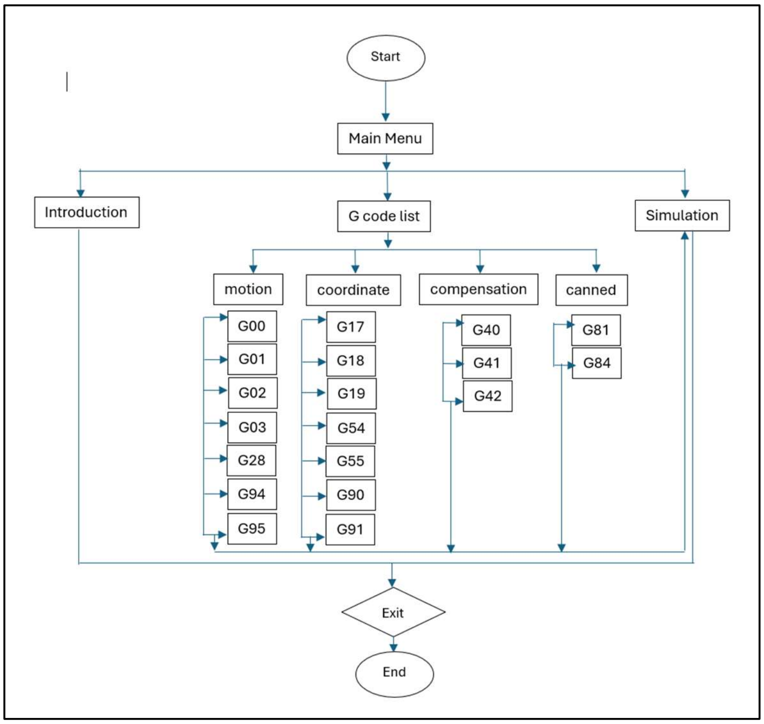
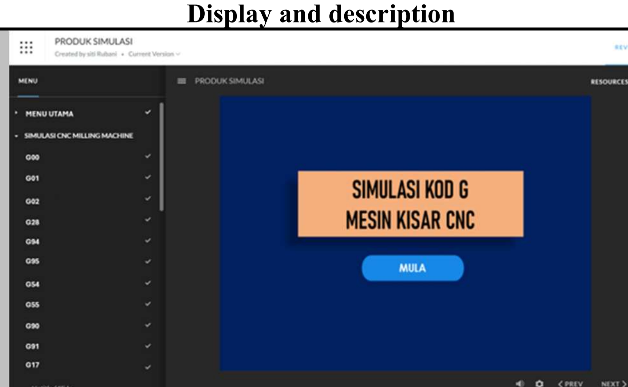


Figure 4. Simulation application's interaction design

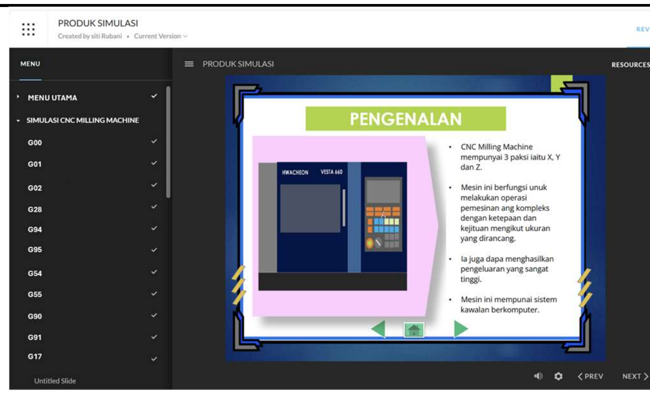
Figure 4 shows the interaction design of the CNC milling machine simulation. The design begins with the main menu where users can select which one from the sub menu they want to learn. Users can navigate through each sub menu to see detailed information and the CNC milling machine movements based on the g-codes on the simulation sub menu. Users can return to main menu or exit the application as needed.

In this phase, the actual development of simulation for g-code movements in CNC milling machines is done using Articulate Storyline 360. Articulate Storyline 360 builds animations based on the design that has been planned. Once development is completed, simulation is tested to ensure that all elements functionally properly. Finally, publish the simulation in Articulate Review 360 from Articulate Storyline 360 and save the file to a website that hosts the simulation. Table 2 is g-code CNC milling machine simulation development

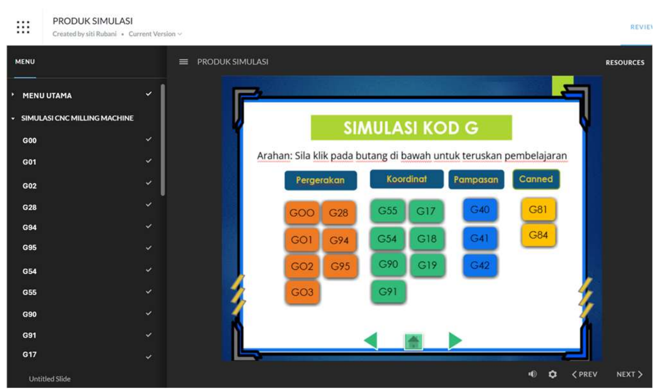
Table 2. G-Ccde CNC milling machine simulation development

No	Interface	Display and description
1.	Main Menu Interface	 In this section, the user needs to press the enter button to start the g-code simulation of the CNC milling machine.

2. Content Interface



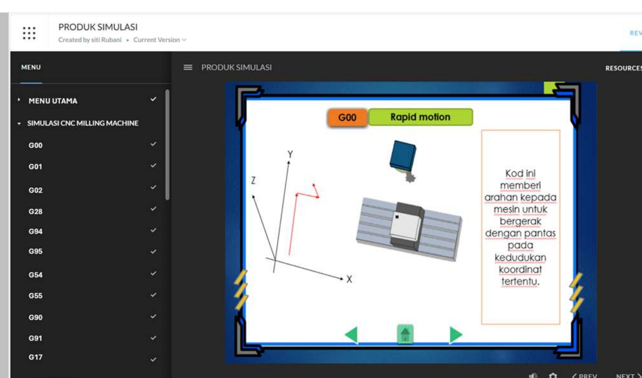
(a)



(b)

Figure 3 (a) and (b) show the content interface of the simulation which involves the selection of g-code to carry out certain operations on the CNC milling machine. On this content interface there is an introduction and instructions asking the student to click on the button provided to continue learning. The content interface in Figure 3 (b) requires the user to click a button to view the simulation. Simulations are categorized based on the type of operations that g-code can perform such as movement, coordinate, compensation, and Canned. The use of different colors for each category helps distinguish different types of operations.

3. Simulation Interface Design



Once the student has selected the code to be learned, the simulation interface display will be shown. The simulation view contains descriptions, graphs and simulations of the movements of the cutting tool points in the machine.

An expert review was conducted to evaluate the content and multimedia quality of the developed simulation. Three experts were consulted: two specializing in content relevant to CNC programming and one in multimedia development. Their feedback provided valuable insights into the strengths of the simulation and highlighted areas for improvement. **Table 3** shows expert feedback received from experts.

Table 3. Expert view

	Expert	View
1.	**Content 1**	1. The use of appropriate sentences and language levels. 2. Appropriate code terms
2.	**Content 2**	1. The addition of video sub-topics to show a clear picture of the real situation.
3.	**Multimedia**	1. Need to add video on title introduction and simulation.

Feedback from content and multimedia experts commended the simulation use of clear and accessible language, noting that the sentence structure and language levels were well-suited to the target audience of vocational students. Expert Content 1 highlighted that the terminology used to describe g-code programming need to recheck for accurate and appropriate. This expert stressed the importance of using appropriate code terms to aid students understanding.

Expert Content 2 suggested the addition of video segments to further support students' comprehension. This expert proposed including video sub-topics within the simulation to illustrate real-world applications of g-code programming, as this could give students a more vivid understanding of CNC machine operations in practical settings. The expert's recommendation aligns with the goal of bridging theoretical and practical learning through visual aids.

In addition to expert feedback, the functionality of the simulation was also assessed through feedback from 30 industrial machining students in Vocational College in Malaysia. The respondent was selected using purposive sampling method focusing on second year diploma students enrolled in the industrial machining program. The questionnaire consisted of two main sections. First is the functionality of simulation in terms of content, while the second item focuses on students' understanding of how the simulation operations. The results of this survey are presented in Table 1 and 2.

Table 4. Functionality of the simulation content

N	Sub item	Percentages	Interpretation
1	The introduction on simulation is interesting?	90%	High
2	The content in simulation is in accordance what you learned now?	100%	High
3	The simulation shown works fine?	100%	High
4	The time allotted in the simulation is appropriate?	80%	High
5	Simulation in g-code CNC milling content is accurate?	87%	High
	Total	91.4%	High

Table 4 show the data analysis related to the functionality of the simulation content. The findings showed that items two and three received the highest agreement, with 100% of the respondents agree that the simulation content is directly relevant to the present learning course material and that the simulation is functioning well. On the other hand, the lowest agreement was obtained with 80% of the students who indicated that it is inappropriate for the time to conduct the simulation. Overall, the data reflects a strong degree of alignment, with a mean interpretation score of 91.4%

Table 5. Students' understanding of simulation operations

N	Sub item	Percentages	Interpretation
1	I understand the language.	100%	High
2	I comprehend the movement of the g-code simulation.	81%	High
3	I understand the explanation shown in simulation.	96%	High
4	I understand the function of the g-codes presented in simulation	84%	High

5	I can accurately follow the sequence of g-code operation as demonstrated in simulation.	76%	Moderate
	Total	87.4%	High

Table 5 show the data analysis related to the students' understanding of simulation operations. The findings showed that item one received the highest agreement, with 100% of the respondents agree that they can understand the language used in simulation. On the other hand, the lowest percentage obtained is 87.4% which indicates that respondents can accurately follow the sequence of g-codes as demonstrated in simulation. Overall, the data indicates a high level of interpretation with mean score of 87.4%.

Discussions

The data analysis demonstrates that integrating simulation technologies into the classroom environment considerably improves both the learning process and user comprehension. This favourable outcome highlights the importance of simulation-based tools in improving the educational experience of Malaysian vocational college students. Such tools are especially useful in subjects that require great visual acuity and the capacity to absorb complicated concepts, such as those using CNC. The development of the CNC milling machine code simulation is an important educational tool. It is main goal is to help students get a basic understanding of g-code programming through visual representation. By allowing students to observe processes in action, the simulation bridges the gap between academic understanding and actual application. According to Yakovlev et.al. (2020), early exposure to g-code in a visual format improves students' capacity to model milling machine operation while also facilitating a greater comprehension of CNC cutting tool movement and function. This type of visual learning is very helpful at turning abstract programming concepts into practical abilities that students can employ in real-world situations. In addition to boosting conceptual knowledge, the simulation gives students hands-on experience, which is vital for grasping the operation of CNC milling machines (Sumardi et. al., 2024). This technique not only improves comprehension but also raises students' confidence in operating CNC machines, better preparing them for the demands of the workforce.

The Design and Development Research (DDR) methodology is used to produce g-code CNC mill simulation, which involves a systematic sequence of phases to ensure that the simulation results are of high quality and useful in the learning process. The DDR model focused on the three main phases: design, development, and evaluation (Mariappan et. al., 2022; Padzil et. al., 2021). The design and development of a g-code CNC mill simulation was done using the Design and Development Research (DDR) model, which entails a series of steps aimed at ensuring that the simulation outcomes developed are of high standards and work effectively during learning. Articulate Storyline 360 was used to develop simulation including multimedia elements such as text, graphic, animation and audio. The researcher used Articulate Storyline 360 for development simulation because it can merge many interactive media into a single application. According to Rafmana and Chotimah (2018), Articulate Storyline 360 functions as a communication tool, presentation and instructional resource. It allows user to create and modify character parts through this application to suit their needs.

The final step in simulation development is to publish the project made in Articulate Storyline 360. After publishing, students can access the simulation through the Articulate Review 360 platform. Articulate Review 360 provides an avenue for students to observe simulated movements of machining operations and g-code CNC milling machine before evaluation carries out. The use of simulation as an educational tool allows students to comprehend more thoroughly and apply practically what has been taught in theory.

Conclusion

The study shows that simulation-based teaching has a big influence on how well students learn g-code for CNC milling machines. This approach offers two main benefits: it makes it easier to grasp complex ideas through moving visuals, and it gives students hands-on practice they often can't get in regular classrooms. The research proves that this method helps students understand the material better. The use of the Design, Development, and Research (DDR) model in this study has made sure the development process was thorough and organized. The team carried out each step of the DDR model by starting with needs analysis and moving through development, implementation, and evaluation. This led to the creation of a strong and reliable educational tool. Being so careful about the method helps to lower the chances of problems or mistakes that might come up later in the project. As a result, the simulation becomes more dependable and valid as a resource for education.

Limitations and Future Studies

The input from student participants gives the researcher useful insights to make the instructional simulation better. The ideas to make the study better focus on tweaking the existing setup to boost the quality of future work. Even though the simulation has been successfully developed, there are some areas still need work to take the overall quality of the simulation up a notch. For future study, the simulation includes view from workbench. It's made the g-code simulation clearer and smoother to understand. To make the simulation process even more clear and effective, we need to fine-tune and broaden the workbench view as needed. These improvements are key to boost the learning impact and make sure the simulation meets top-notch teaching standards.

Acknowledgment

1. This work was supported by the Universiti Tun Hussein Onn Malaysia, Johor using TIER 1 Grant (Q502).
2. We would like to express our sincere gratitude to our colleagues from Focus Group Instructional Design Technology (IDT) for who provided insight and expertise that greatly assisted the research.

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