G-Code Machina: A Serious Game for G-code and CNC Machine Operation Training

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***Abstract*—In this paper, we present a desktop-based CNC machining training system developed as a serious game for CNC manufacturing motivating young digital-ready users to train in the machining sector. The proposed serious game trains users to write G-code and set up virtual machines for completing Milling and Turning tasks, contrary to previous work mainly focusing on machining simulations. G-code is a simple and usable low-level command set for manufacturing complex objects without prior knowledge of Computer-Aided Manufacturing (CAM) systems. The proposed CNC machining serious game can be used as a standalone introductory training application before being involved with CNC manufacturing. It contains CNC machining and G-code tutorials explaining processes without the need for a book or the assistance from a trainer. The user can select to train in turning and milling machines. The system adapts to each user's progression and performance, assigning missions to a user when mistakes are continuous, while hastening the progress of an experienced user to more advanced missions. The user can check the correctness of the code they have written and receive feedback in relation to potential mistakes.**

***Index Terms*—Industrial training, Digital simulation, Virtual manufacturing, Virtual machining, Visualization**

I. Introduction

Training new personnel for Computer Numerical Control (CNC) manufacturing is often a tedious operation. Practice under real-world machinery is expensive, consuming vital system's resources and, in some cases, dangerous for the trainee [1]. G-code programs guide the machining process, written in a computer or machine controller and loaded to a machine. A safer alternative for training uses simulated factories or training environments. The concept of a digital factory can be defined as an interactive 3D environment supporting modeling, communications and operation of manufacturing [2]. Previous studies indicate that virtual training is effective as the trainee is guided through complex product manufacturing [3], [4]. While there are plenty of gamified virtual simulations that aid in manufacturing training and mainly focus on safety tasks [5] or manual operation [6], the task of creating a serious game focused on writing G-code is technically challenging. Potential trainees often have no previous programming knowledge. It is significant that they learn how to write efficient G-code programs, not just correct ones.

In this paper, we present an innovative desktop-based CNC machining training procedure, created as a serious game for CNC manufacturing training. The proposed serious game prepares the trainee in writing G-code and setting up virtual machines for completing milling and turning tasks. The serious game environment offers a complete training procedure, based on the flow of a modern game. The trainee is offered tutorials and step by step guidance and is then asked to complete further manufacturing tasks using the knowledge acquired. Based on the target audience, the trainee can learn either milling or turning procedures independently. Our training procedure works as a standalone training system without the need for a supervisor or trainer to be present. Our work is focused on G-code training and basic machine setup as communicated by an engaging 3D environment and a streamlined training process. The trainee is assigned to write the correct G-code while undertaking turning or milling missions known as tasks. The trainee reads the provided documentation and the mission specifications and then sets up the milling or turning machinery with the appropriate cutting tools and manufacturing materials for each mission. The game presented is an introductory step towards innovative CNC manufacturing

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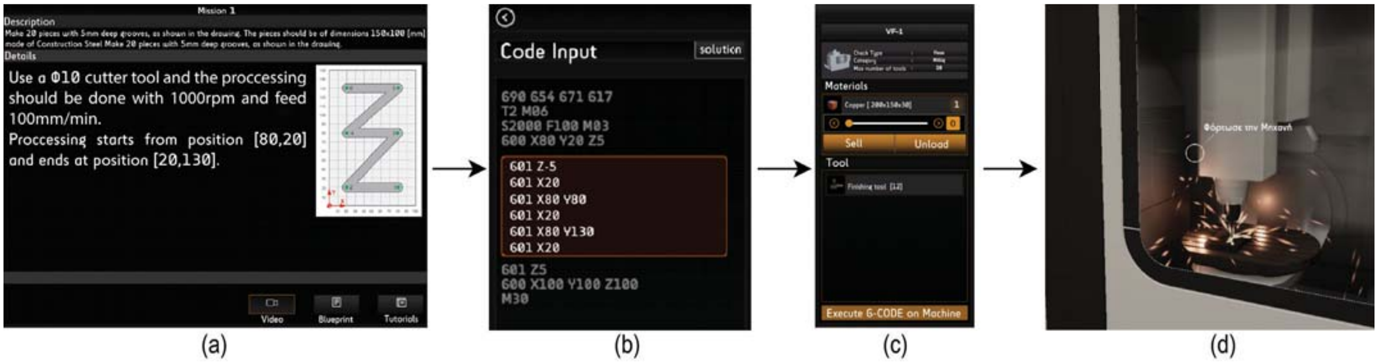


Fig. 1: An overview of the training procedure proposed. The player accepts a mission (a), writes the correct G-code (b), loads cutting tools and materials on the machine (c) and finally cuts the requested object. The result of the final object is then shown inside the milling or turning machine (d).

training for trainees with minimal or no prior knowledge, such as bachelor engineering students without an engineering degree. They are going to evolve into a new generation of technically proficient manufacturing workers.

II. Related Work

A. The manufacturing process

Controlling a real-world CNC machine is possible through three methods. The simplest one is the use of a Numerical Control (NC) unit, which allows for manual control through the use of an interface of buttons and controls. The second method is the use of commands written in a predefined format named ”G-code”. G-code programs are written on a computer or machine controller and loaded to a machine. The final method is the use of Computer-Aided Design (CAD) and Computer-Aided Manufacturing (CAM) software that convert a virtual 3D design into G-code. Among these three methods, using an NC unit is optimal for simple manufacturing work, while CAM programs are used by 3D designers and not average users. G-code is a simple and usable low-level command set for the creation of both simple and complex objects.

By using G-code, an operator instructs a machine how to manufacture a desired object. This involves instructing the machine in relation to which motors to move, where to move and what path to follow. The most common use cases include cutting jobs, such as milling or cutting where a tool or cutting material is moved through a tool path cutting away unwanted material while leaving the desired work piece. Similarly, instead of cutting tools the same operations can be performed in additive manufacturing machines, such as in 3D printers that photo-plot objects instead of cutting.

Milling and turning are two of the most widely used machinery in manufacturing [8]. Turning machines use a non-rotary cutting tool that moves more or less linearly along 1 to 3 axes of motion while cutting a rotating stock material. Cutting can be performed on the outside or the inside of the material to produce tubular components of various geometries. Milling on the other hand advances a rotary cutting tool into a stock material in varying directions on several axes and with varying feed rate.

B. CNC training

Previous work related to CNC training has focused on simulating the machining process and realistic physics [7] including virtual object prototyping [9] and factory layout simulations [10]. Systems for showcasing manufacturing training tools [11] offered only a mere visualisation of 3D objects produced by a CAD/CAM simulation of the G-code or focused on the physical handling of CNC machines offering connection with external G-code interpreters, omitting any G-code training [12]. The challenge is to produce, for the first time, a complete training system based on setting up CNC machinery and writing G-code, in a standalone environment without the need for external software.

Previous studies that use serious games in manufacturing and other fields have shown positive results as effective training environment [25], [18]. In manufacturing, trainees can take their time and learn various machine shop operations with less pressure and stronger motivation. Serious games cannot replace training in manufacturing as performed in the actual machine shop [5]. Instead, serious games should focus on engaging learning in specific aspects of the manufacturing process instead of attempting to fully replicate hands-on training in an actual machine shop. Studies have shown that trainees with gaming experience took significantly less time in completing their virtual training compared to trainees with no previous gaming experience. Having no gaming experience, though, did not hinder the overall understanding of the manufacturing operation [13].

Other machine training approaches were focused on Virtual Reality (VR) development [4], [24]. VR applications tend to focus on the interaction with 3D objects and machinery in a realistic manner and not on the significant process of writing G-code requiring a keyboard for optimal interaction. An alternative solution to keyboard input employed a real-world NC-unit along with a virtual CNC machine model (NC-VR coupling) [6]. This solution allowed for manual control of the simulation instead of G-code programming. Another system combined CAD software with VR simulations in order to utilise the high accuracy of CAD software and the presentation of a VR environment in order to achieve highly detailed simulations in an immersive environment. Such applications have multiple constraints imposed by both the CAD and VR systems while also requiring high computational power to use both systems at once [14].

Previous training systems combine both desktop simulations of an assembly line combined with a VR simulation for operating individual machinery. Such simulations are not focused on training a single worker but a group of workers such as factory planners, decision makers and assembly workers all at once [15]. In another study, a serious game was developed to educate trainees in all layers of a manufacturing hierarchy, from the field layer of factory workers up to the enterprise layer that manages the whole factory. Such systems are only used as simulations to evaluate decision making and are not used as educational material [16]. Other studies view the virtual factory through a holistic approach in order to optimise the production process including steps from optimally modelling the virtual factory floor and performing execution and sound simulations to even virtual tours of modeled factories [17].

Finally, other training approaches attempt to combine traditional education through books with gamified machining elements presented in Augmented Reality (AR) superimposed on a real-world text book [18]. Such applications tend to combine traditional training materials such as educational textbooks with aspects of games that provide immersion or improved understanding of the teaching material. These are often used inside classrooms [19] or real workstations [20] making the training process more enjoyable. However, they do not overcome existing problems, such as safety concerns and mostly provide a pleasant visualization of specific machining elements rather than complete training.

We propose a complete gamified 3D training system for G-code programming which offers specific technical missions of varying difficulty in milling and turning, involving the selection of tools and guiding the trainee to write the correct G-code. Studies show that gamified applications are perceived as easier and more enjoyable to use than simulations motivating mainly young users to engage with training [21].

III. Implementation

We will now describe the main components of our CNC machining training system which comprises of a 3D representation of a machine shop inclusive of milling and turning machinery, tools and materials storage areas as well as a wide range of tutorials for G-code training and G-code training missions. The trainee is tasked with completing the so-called training missions using turning and milling machines in order to manufacture objects of a requested shape. By using a blueprint of the requested object and a list of appropriate manufacturing parameters, such as the selection of the cutting tool or material, the trainee learns how to write correct G-code, gets feedback for G-code mistakes and prepares the CNC

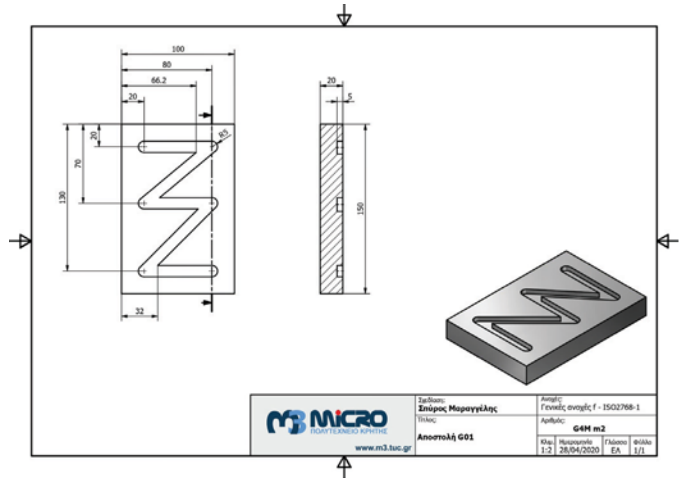


Fig. 2: Mechanical drawing.

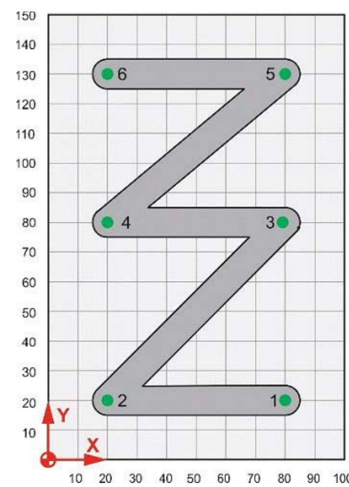


Fig. 3: Cutting path diagram.

machines for the cutting process. During the course of the game, the trainee will learn G-code commands progressively as they complete more missions.

The proposed CNC machining serious game can be used as a standalone training application. It contains CNC machining and G-code documentation explaining processes without the need for a book or the assistance from a trainer. The system is personalised providing detailed feedback signifying the trainee's progression.

A. The traditional manufacturing process

In order to design an innovative game for efficient machining training, an extensive interview obtaining feedback concerning machining educational processes was conducted involving university faculty in a university machining lab where undergraduate and postgraduate students are educated in the field of Mechanical Engineering. During this interview, information regarding standard teaching methods was obtained involving theory and documentation and the limitations of education through software-based CAD-CAM simulation were discussed.

Researchers in the lab described the traditional hands-on procedure of training undergraduates using G-code and CNC machines, where each student performs a hands-on operation to manufacture a requested piece on a milling or turning machine. As the number of students entering university education in machining exceeds 150 every year and the number of milling and turning machinery available is limited, real-world training in manufacturing is limited. In addition, the risk of a workplace accident from an inexperienced student is high, thus every student requires constant supervision. In most cases, during the course of a machining lesson, the students use simulators to write G-code. Simulators, though, lack the sense of an actual machine shop and students are often overwhelmed when performing a task on actual machinery. In addition, we obtained hands-on experience inside an actual machine shop in the manufacturing floor of the university lab.

After the interview, a brainstorming session was held where we streamlined the steps of the manufacturing process in a gamified scenario. Overall, we can simplify the process of manufacturing in three distinct steps: Receiving a manufacturing request from a client or professor with the appropriate data, writing the G-code that produces the requested object and finally adding the appropriate cutting tool and cutting material to the machine. While there are other steps such as performing simple maintenance to a malfunctioning machine or cleaning the machine after each use, we decided to omit such side steps for the sake of simplicity and focus on the educational processes involving these three distinct steps.

When a client or professor in a machining laboratory requests an object, they provide the employee or trainee with the shape of the requested object, the material and the relevant quantity. The shape of the object is described in a 2D mechanical drawing (fig. 2) depicting a representation of the object through views and providing the required dimensions. The material of the object is extracted from the constraints imposed by the object's usage, e.g. tension, elasticity, heat resistance etc, but the appropriate material and quantity is often chosen by the client. Based on the requested material and blueprint details, the employee or trainee must determine the initial parameters of the cutting procedure such as the maximum allowed spindle speed or maximum feed rate, which are provided by the tool manufacturers for all given tools and materials. Next, the mechanical drawing is translated by the employee into G-code, which consists of simple motions, such as a sequence of straight line commands or circular commands (fig. 3). For more complex objects a CAM software is required.

After the cutting path is determined, the G-code programming step is the translation of each step of the execution process to the appropriate G-code commands. Since each G-code command requires different parameters and is a low level programming language, the process is a tedious step by step lookup through a manual (fig. 7) so that the correct syntax for each command is determined, becoming easier through practice and memorisation. The evaluation of the G-code is accomplished through CAM software such as Siemens NX, which produces the programmed 3D path and the final model that will be manufactured.

Finally, the process is completed by adding the appropriate tool and material to the machine and executing the program. The employee then monitors the cutting process making necessary adjustments, such as adding new cutting materials after each cut or adding new cutting tools after they are worn out.

B. 3D CNC Machine shop

In this paper, we aim to present an interactive 3D gaming environment involving training for G-code execution. The 3D CNC Machine Shop is the core environment (fig. 5). The design of the space was inspired by a real-world machine shop layout but did not fully simulate one, resembling large spaces that allow free navigation which is appealing to gamers. Machine shop experts preferred a space which did not fully resemble an actual machine shop, but one that offered stronger visual satisfaction. They expected that visual satisfaction would offer incentive for more 'play time' and, thus, training time without exhausting the trainee.

The virtual machine shop of our training system comprises of three key areas required for gameplay. The first is an office inside which the trainee can get machining training missions and write G-code on a virtual computer. The second area is the main manufacturing floor where the milling and turning machines reside. The third area is the storage, inside which the trainee can go and retrieve cutting tools and materials (fig. 5). Additional areas were filled with secondary objects such as a lounging area or storage cabinets that are not essential to the manufacturing process but result in a highly compelling and realistic gaming experience. During the course of the training process, the trainee roams around the machine shop and interacts with specific User Interfaces (UIs) allowing reading documentation, obtaining new missions, writing the G-code, buying new tools and materials as well as slotting tools and materials inside machines.

C. The training procedure

The training starts from either turning or milling processes. The trainee selects to start with either a turning machine or a milling machine at the start of the game. They can unlock more machines of the other type during the course of the game if they desire. Initially, the trainees are given instructions on how to play the game and interact with virtual objects. The first time the trainees enter the training environment, they are greeted by a tutorial that introduces the basic mechanics of the game. An animated tour of the virtual machine shop is presented including a short explanation of each key component of the factory as an engaging virtual tour of the factory. The main machining tutorials follow including the first two G-code commands required to complete the first missions. After completing the tutorial, the trainee accepts new training missions instructing to manufacture various objects utilizing the G-code commands learnt.

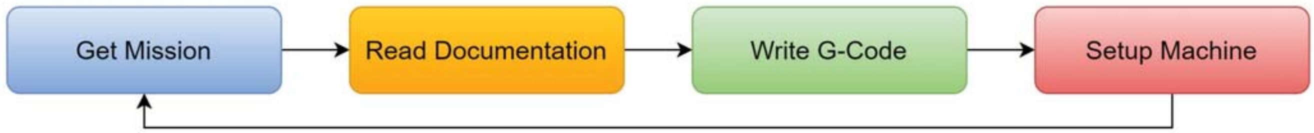


Fig. 4: The training procedure.

Fig. 5: The 3D CNC machine shop.

After each mission is completed, the trainee is awarded with virtual ”Experience” and ”Gold”. The trainee carries on completing missions of increasing difficulty based on their ”Experience”. They can choose to unlock more machines of a different type, for example a new milling machine or a new turning machine in order to continue their training by using ”Gold”. Each mission is comprised of four distinct steps (fig. 4). The trainee initially accepts a new mission which contains the request to manufacture a specific object. The trainee then proceeds to read any appropriate documentation and write the correct G-code that produces the requested object. When the written code is correct the trainee proceeds to the storage in order to purchase the appropriate cutting tools and materials and then load them to the milling or turning machine on the manufacturing floor.

a) Get mission: The trainee accepts a new mission by reading the mission description accompanied by the cutting path blueprint as seen in fig. 1a. The mission description is also accompanied by the mechanical drawing seen in fig. 2 which can be viewed by the respective button on the same interface. Through the same interface, the trainee can also view the documentation interface through a second button.

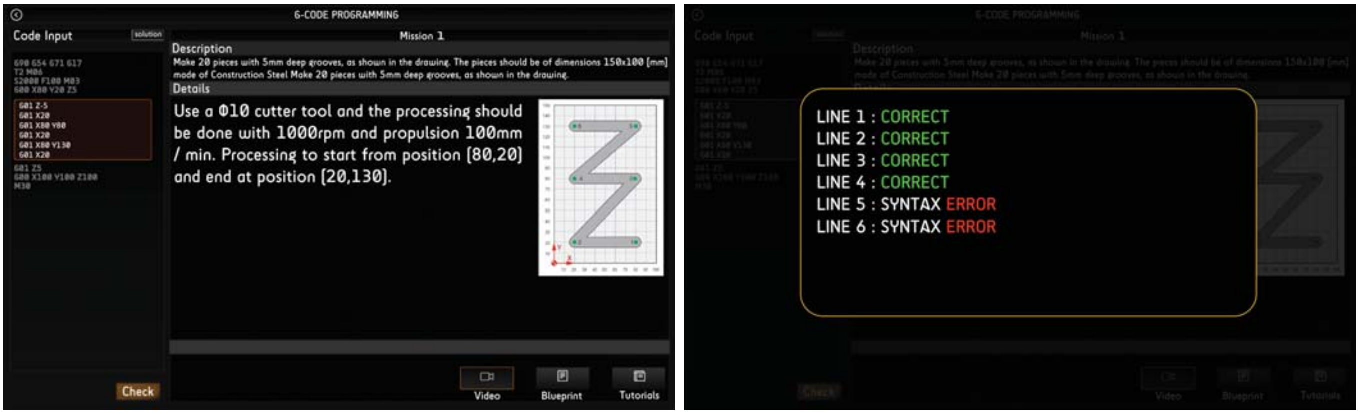
b) Read documentation: The documentation interface contains pages from a G-code textbook as authored by faculty of the university machining laboratory, used as a reference material for undergraduate students (fig. 7). The documentation contains a selection of tabs, each providing documentation regarding the general operation of the machines, a specific G-code command syntax or a full example of a specific G-code command. The pages shown in the documentation tab are filtered, showing only the pages including related information for a requested mission while also highlighting any unread material, therefore, helping the students focus and understand the necessary documentation without having to search for it in an effort to reduce frustration.

c) Write G-code.: The G-code programming interface includes a code input interface along the mission description interface (see Fig. 6a). During prototyping, user feedback communicated that following an optimal tool path shouldn’t be optional. It was significant that the trainees learn how to efficiently write G-code, not simply correctly. As is, the initialization and ending of the G-code is pre-written and the trainees are asked to write the central portion of the main cutting process by following a given path blueprint. The only code that is, therefore, checked for correctness is the core code of the main cutting process. The trainee can check the correctness of the code they have written and receive feedback in relation to potential mistakes (fig. 6b). The correct cutting path and useful information about each mission are always visible to allow the trainee to view them while writing the G-code. The trainees can try as many times as they need in order to complete the mission without any time limitations or penalty or machine failure as in the real-world.

d) Machine setup: After the trainees have written and corrected their code, the final step is to setup the physical machine for the process. The trainee is asked to add the appropriate cutting tool and stock material on the machine, as stated in the mission description. The trainee can walk around heading for the storage in order to buy the appropriate cutting tools (fig. 8a) and materials (fig. 8b). The trainees, then, interact with the actual CNC machine and ”slot” the tools and materials on the machine before executing the code (fig. 1c). Allowing for the trainee to walk around the machine shop and interact with machinery is not necessary for G-code training but it provides trainees with a higher sense of immersion. Interacting with machinery and receiving minimal feedback while executing a program allows the trainees to feel a higher sense of accomplishment as opposed to displaying a simple congratulatory message.

IV. Evaluation

We conducted a pilot evaluation to assess the usability and training performance of our training environment for machining processes. As on-site evaluation was not possible due to the COVID-19 pandemic, we performed a hands off remote testing. We packaged a standalone executable of our



(a) (b)

Fig. 6: The G-code interface (a). Programming interface including the G-code input field on the left and mission info on the right. Feedback after the "Check" button is pressed (b).

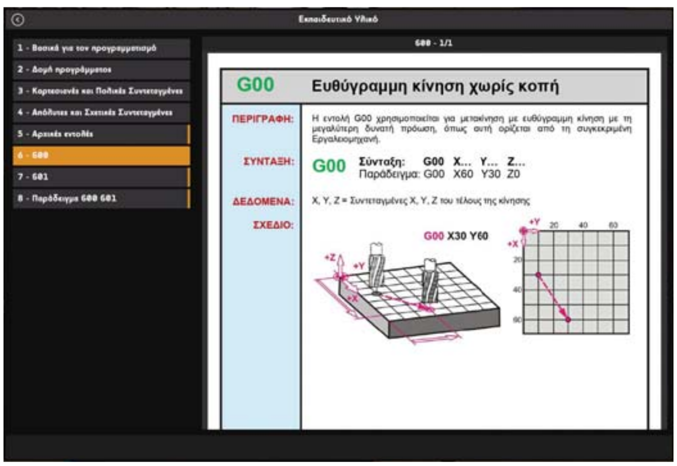


Fig. 7: The documentation interface.

game which contained 13 milling missions that was administered to users with minimal information. We estimated the maximum duration for completing all 13 missions to be a maximum of 4 hours for someone with no previous knowledge of G-code. For the sake of prototyping, a "Solution" button was added on the G-code input interface (fig. 6a above the Code Input field) for cases when the trainees struggled. In case the "Solution" button was pressed, the correct G-code would appear automatically, but the user was not awarded "experience" for progressing further in the game and would be reassigned the same mission at a later time. Based on this testing procedure, we evaluated the following hypothesis:

- (H1) Our serious game can be used as a standalone training system without the need for an instructor.
- (H2) By using a serious game as a formal training tool for machining processes, even trainees without any previous experience in milling or writing G-code could be motivated to learn due to the more enjoyable environment.

A. Users

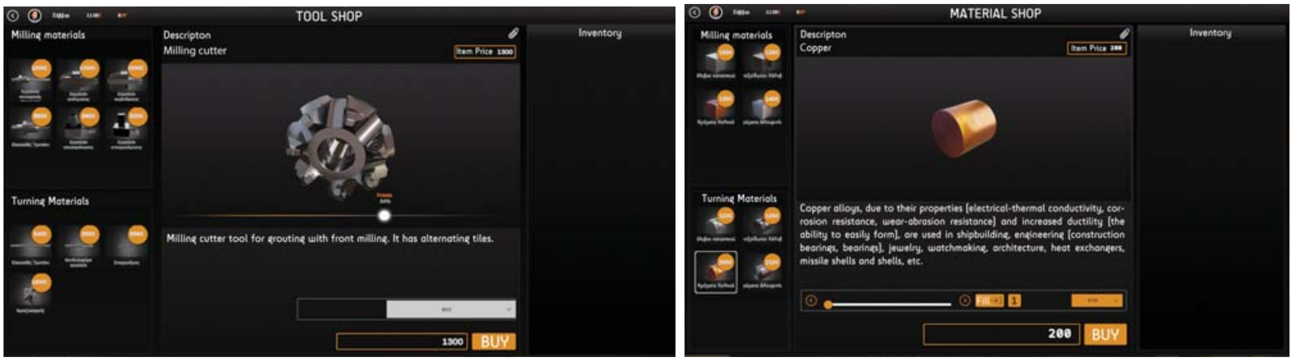
Users were free to play for as long as they desired over a span of 1 week with a minimum set of instructions that included:

- (1) The game teaches the basics about writing G-code. Instructions on how to play the game or write G-code are included in the game.
- (2) If you are stuck at any point, you can press the "Solution" button, but if you do, you will be asked to redo the same mission later on.
- (3) You are free to play for as long as you like, but you are requested to complete at least 1 mission without the use of the "Solution" button and play for a minimum of 1 hour during the span of 1 week.
- (4) After playing the game, you are requested to fill out a questionnaire describing your experience in the game. There is also a field for qualitative feedback where you can write about any issues, bugs, or thoughts on how to improve the training procedure. You are also requested to provide your game's save data.

We selected a variety of users including both experts (faculty or doctorate candidates in the field) and users with no previous experience in milling or G-code (undergraduate students). 9 users fully completed our tasks including 2 experts and 7 users with no G-code experience. 2 users were female and 7 users male. All but one users were in the age range of 25-40 years and one user was above 41 years old. We include these 9 users in our data analysis. There was a number of other users who partially completed our tasks because of low spec computing equipment who are not going to be included in the data analysis. We will take into consideration only their qualitative comments and user feedback.

B. Data collection

We evaluate each user's performance through a mixture of quantitative and qualitative results based on surveys as well as



(a) (b)

Fig. 8: The tool shop (a) and material shop (b) interfaces. On the left panel various tools and materials are shown, on the central panel there is a visual representation of the selected tool or material along with a description. On the bottom side there is a buy button with a selection related to the dimensions of the tool or material along a quantity slider for the materials.

general feedback in the form of free form comments. Quantitative results include the time played, number of missions completed without the use of the ”Solution” button, as well as the average time spent on each mission. Qualitative results were based on two surveys including the NASA Task Load Index (TLX) [22] survey for perceived workload and an 8-part System Usability Survey (SUS) [23], both of which were graded on a 7-point Likert scale (1= very low, 4= neutral, 7= very high).

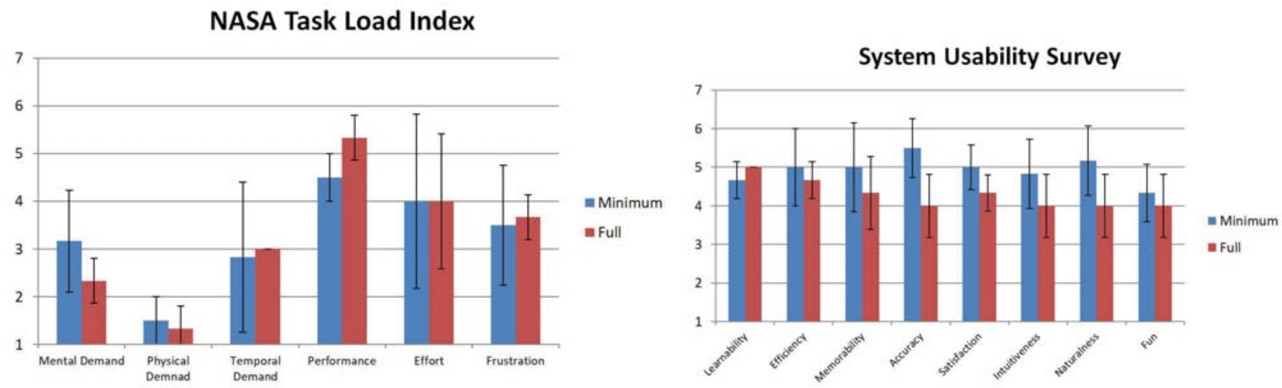
The NASA TLX assesses perceived performance effectiveness on 6 aspects: *Mental demand* (how mentally demanding was the task?), *Physical demand* (how physically demanding was the task?), *Temporal demand* (how hurried or rushed was the pace of the task?), *Performance* (how successful were you in accomplishing what you were asked to do?), *Effort* (How hard did you have to work to accomplish your level of performance?) and *Frustration* (How insecure, discouraged, irritated, stressed and annoyed were you?). The SUS assessed training efficiency in 8 aspects: *Learnability* (How easy was it to learn using each environment?), *Efficiency* (How efficient was the learning process?), *Memorability* (After which experiment did you feel more confident in redoing the same task in the real world?), *Accuracy* (How accurate or responsive was each system?), *Satisfaction* (Overall, how satisfied were you with each setup?), *Intuitiveness* (How intuitive was the usage and interaction of each system?) and *Fun* (Did you enjoy playing the game?). Finally, we separated bug reports from useful usability and qualitative feedback and categorised feedback in four categories: *Training procedure*, *Virtual factory*, *User Interfaces (UIs)* and *Documentation*.

C. Results

Based on the qualitative results, we found that 6 users played until they met the minimum criteria of 1 mission and 1 hour played. 3 users completed all 13 missions until the end. As these two parties experienced the training procedure differently, we decided to separate the results in two categories. Users who met the minimum requirements completed an average of 1.6 missions (SD 0.4) without using the ”Solution” button and played for an average duration of 1 hour and 20 minutes (SD 20 min) while users that finished all missions completed an average of 11.3 missions (SD 0.7) and played for an average duration of 1 hour and 50 minutes (SD 30 min).

Through the Nasa TLX we can see that users who completed all missions had low Mental (avg. 2.3, SD 0.4) and Physical demand (avg 1.3, SD 0.4), while having slightly higher Temporal Demand (avg. 3, SD 0). The perceived performance levels were high (avg. 5.3, SD 0.47) but the Effort (avg. 4, SD 1.4) and Frustration (avg. 3.6, SD 0.47) levels were average. Users who completed the minimum requirements followed similar levels of Physical demand (avg. 1.5, SD 0.5), while they experienced more Mental demand (avg. 3.16, SD 1.06) and higher variance in levels of Temporal demand (avg. 2.83, SD 1.57). They also perceived lower Performance (avg. 4.5 SD 0.5) levels and similar Effort (avg. 4, SD 1.82) and Frustration (avg. 3.5, SD 1.25) levels with increased variance. Overall, we can see that players who played the full game had less variance in their results, while those that played for the minimum duration were more conflicted, some adapted to the training process at a fast pace while others had to put more effort and time in completing missions.

The SUS shows that users that completed all missions demonstrated high levels of Learnability (avg 5, SD 0) and Efficiency (avg. 4.66, SD 0.47) while they show average levels of Memorability (avg 4.33, SD 0.94), Accuracy (avg 4, SD 0.81), Satisfaction (avg 4.33, SD 0.47), Naturalness (avg 4, SD 0.81) and Fun (avg 4, SD 0.8). On the other hand, players that completed the minimum requirements show lower levels of Learnability (avg 4.66, SD 0.47) and high levels of Efficiency (avg 5, SD 1), Memorability (avg 5, SD 1.15), Accuracy (avg 5.5, SD 0.76), Satisfaction (avg 5, SD 0.57), Intuitiveness (avg 4.83, SD 0.89), Naturalness (avg 5.16, SD 0.89) and Fun (avg 4.3, SD 0.8). Through these results we can see that the more missions the users complete, the better they are able to learn, while the users that completed the minimum requirements focused more on the ”gamified” aspects of the game such as



(a) (b)

Fig. 9: Results from the (a) Nasa TLX Survey and (b) SUS.

the Naturalness and Intuitiveness of playing the game rather than the learning process.

D. General Feedback

Regarding the training process, although our game provides detailed tutorials and guidance throughout the first mission, users reported that they needed more guidance to familiarise themselves with the training procedure. After completing the first mission, many users struggled to remember the instructions offered during the first mission or skipped the initial instructions, therefore, they were confused and frustrated during the second mission and on wards. After completing a few missions, users reported that the training process was more enjoyable. Two users that only completed the minimum requirements stated that they felt discouraged to continue due to this reason. When it came to the virtual factory and the UIs, the trainees reported they would prefer even more enhanced visual material and spatial sounds in order to make the environment more immersive, but the core objects of the virtual factory were intuitive and well designed. Furthermore, users felt that the mission descriptions that were communicated in plain text were confusing and would prefer the content to be organised in streamlined "bullet points" with clear instructions.

Finally, users who had technical difficulties provided us with the hardware specifications of their computers. Based on this feedback, we identified that users with 4GB of RAM could not even start the game as it required a minimum of 6GB of memory space. For the game to be functional, a computer should include an external GPU and should be of 6th generation or more recent.

V. Conclusion and Future Work

This paper presents an innovative CNC programming training system for turning and milling machines for G-code education. Our training system is designed as a serious game specifically for CNC programming training. The serious game includes a wide range of G-code missions that introduce the basics of coding progressively. Based on the serious game for CNC programming detailed here, the user completes manufacturing missions by writing the appropriate G-code and selects the appropriate manufacturing tools and materials for each job, while being offered feedback. Continuous feedback from machining experts has been integrated, in relation to the type of milling and turning operations, G-code variants. Related user interface succession has being incorporated in the system.

Based on the pilot evaluation of our training process we can summarise that:

- Users often required a lengthier tutorial for the game providing to-the-point instructions.
- Users that persisted through the first few missions show significant improvements in their performance after completing their first two or three missions.

Our evaluation showed that the instructions in relation to the tutorial training before starting the game are central to successful progress. Many users either ignored the tutorial's instructions or simply forgot certain steps after the completion of the tutorial, resulting in them getting stuck in subsequent missions. Users that completed more than three missions showed greater understanding of the game and greater performance in completing further missions. Thus, we can surmise that our training process is well designed. Trainees required detailed tutorials while learning the basics of the virtual environment as well as step by step feedback during a mission. Our pilot study confirms that the core training procedure can be used for G-code training without any feedback from a trainer.

Our current system was designed as a gamified learning environment that borrows elements from traditional education. All of our negative feedback was targeted towards the secondary parameters of the training process such as the tutorial, guidance inside the virtual space and the high hardware requirements.

Future work will include a new tutorial system which would provide even more detailed feedback for every step. Extensive user studies in the university training environment when students and faculty return on-site after the pandemic ends, will uncover processes which could optimally improve the training system's usability.

Additional future work will include optimisation to the serious game to be used as a remote teaching environment. Students should be able to play the game on their own hardware and at their leisure. A second evaluation in a remote setting which would include a larger group of students would provide ample feedback on the effectiveness of our game as a standalone training environment as an alternative to on-site learning.

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