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3D PRINTING TRAINING IN A DIGITAL VR-BASED ENVIRONMENT

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Abstract
Virtual reality (VR) environments have been used for a variety of training purposes both in academia and industry. The present paper examines the key stages of the 3D printing process and explores the use of VR technology for the development of a digital training environment for both entry-level and advanced participants. Users are led through a digital roadmap with the aim of following a structured training course in 3D printing technology, while guiding messages are occasionally presented through the course. First, a series of educational materials introduces the 3D printing technology along with the appropriate fabrication parameters needed. Next, the evaluation of the 3D printed models, together with the presentation of possible malfunctions, offers advanced knowledge to experienced users on how to identify and avoid common printing pitfalls. In addition, computer aided design (Blender™) and slicing (Ultimaker Cura™) pieces of software are presented to stress the appropriate file formats used in the whole process. Then, users can virtually observe the 3D printing simulation based on the generated G-code and select different layers of the geometry to be presented i.e. infill, support, skin, skirt. Finally, the preparation and execution of the printing process enable users to learn the operation of a specific large-scale fused filament fabrication (FFF) 3D printer. An early evaluation of the trainees' satisfaction is conducted to assess the effectiveness of the training approach.
Keywords: *Virtual Reality, 3D Printing, Additive Manufacturing, Training, Immersive Technologies*

Introduction

Nowadays, the use of Virtual Reality (VR) has become increasingly widespread, creating new opportunities, particularly in the field of product design training, where educational materials are delivered through immersive digital environments based on Computer-Aided Design (CAD) systems (Minaoglou et al., 2025; Kourmouki et al., 2025). More specifically, a growing area of application is engineering education, where processes such as 3D printing provide opportunities for interactive and collaborative learning. In this context, VR-based applications are particularly valuable in supporting users to understand the fundamental concepts and stages of the 3D printing process, within a safe and controlled virtual environment.

State of the Art

3D printing has become increasingly important across various domains, particularly in engineering education, as it has transformed how students design, test and understand engineering concepts, while also promoting creativity and hands-on learning (Nazha, 2021**)**. In more detail, Celorrio-Barragué et al. investigated the integration of FDM-based 3D printing into Structural Engineering education to support the visualization and conceptual purposes, of topics such as stiffness and stiffness methods, theory of structures and structural detailing. The authors implemented the approach in two undergraduate courses, through five structured laboratory activities, in which students designed and utilized 3D printed models for tensile testing, truss analysis, plane frame stiffness evaluation, joint visualization and reinforced concrete detailing. Overall, the study reports that the inclusion of the 3D printing technology increases student engagement, motivation and practical advantages compared to traditional laboratory kits (Celorrio-Barragué et al., 2019). Meanwhile, for better integration of 3D printing to educational purposes, Günther proposes an educational workshop designed to teach students the fundamentals of 3D printing through a sequence of progressively complex tasks. The approach is structured around a series of assignments that guide the students through the entire additive manufacturing workflow, including printer setup and CAD modeling to slicing and fabrication (Günther, 2020**)**. Similarly, Korenova et al., investigated the didactic potential of 3D modeling and 3D printing in teacher education. Their theoretical framework involved the TPACK framework, constructivist learning theory and the 5E instructional model, while throughout a qualitative content analysis of student projects and reflections, the study identified four thematic dimensions: didactic orientation, technological engagement, constructivist learning design and practical implementation reasoning (Korenova et al., 2025).

Although 3D printing has been widely recognized for its educational potential, in many cases, its practical implementation remains challenging. More specifically De la Cruz-Campos et al. highlight that the implementation of 3D printing in education is often constrained by the lack of technical skills and resources among both students and teachers, including limited preparation time, cost and access to materials and the complexity of required tools. In this context, alternative and complementary technologies are being explored. While traditional teaching methodologies remain effective, emerging immersive approaches such as VR learning are being developed to enhance education through interactive digital environments (De La Cruz Campos et al., 2022). In a broader context, Sakkas et al. demonstrate that VR can serve as an educational tool for teaching geometric concepts. In particular, their study highlights that VR enables students to visualize, observe and explore 3D geometric shapes from different perspectives, thereby improving their understanding (Sakkas et al., 2022). In the field of 3D printing teaching, Singhal et al, highlight the advancement of additive manufacturing education through the integration of virtual laboratories as a complementary teaching approach. They developed an open-access, web-based 3D Printing Virtual Simulation Lab structured around a threefold pedagogical framework, the "Align-Act-Assess" model. The platform consists of 12 interactive modules covering the key aspects of 3D printing, including printer anatomy, assembly, major additive manufacturing processes and pre/post processing techniques. Through a comparative case study involving undergraduate engineering students, the authors demonstrate that the virtual lab boosts students' confidence, flexibility in parameter experimentation, and overall learning experience (Singhal et al., 2024). Similarly, Henstrom et al. employed a structured experimental design, assessing cognitive load, spatial ability, usability and user experience, to ensure a comprehensive comparison between the two approaches. Revealing that VR reduced the perceived effort, while offering a significantly more engaging and immersive experience compared to traditional methods. Additionally, they added safety related eligibility criteria to ensure a safe and reliable evaluation environment. Participants were carefully selected based on specific eligibility criteria, including being enrolled in the course, not being prone to motion sickness, seizures, or having implanted medical devices (Henstrom et al., 2024).

Several other studies have investigated the use of VR environments to enhance spatial understanding in technical drawing education. Pohlmann et al. present the development and evaluation of a VR and Augmented Reality (AR) based-learning system called DT3D, aimed at supporting the teaching of technical drawing in higher education. The tool was evaluated by students

using the Learning Objective Review Instrument (LORI) framework, indicating improvements in spatial understanding and overall student engagement (Pohlmann et al., 2023). Similarly, another study suggested that VR can provide comparable learning outcomes and proposed a structured design framework for converting existing teaching activities into immersive VR environments, consisting of three phases: the "As-is" analysis phase, iterative development phase and evaluation phase (Henstrom et al., 2023).

In the context of using VR to support 3D printing education, many techniques have been proposed to improve both learning effectiveness and user experience. Balzerkiewitz et al. propose a systematic and holistic approach for integrating VR into engineering and design education. Their methodology follows a workshop-based and student-centered approach aligned with constructivist learning principles. The teaching concept is structured based on the four-component instructional design model, consisting of the definition of learning tasks, the establishment of performance standards, the sequence of the tasks, the design of supportive and procedural information and part task practice (Balzerkiewitz et al., 2024). In comparative terms, Beveridge et al. present a case study that follows a methodological framework in which learning objectives and user needs are integrated in the process. The framework consists of three main phases: pre-design, design and development (Beveridge et al., 2023). Sopapradit and Wannapiroon propose a conceptual model based on a STEAM approach, integrating digital fabrication laboratories to support creative product development (Sopapradit and Wannapiroon, 2022). Likewise, Marjanovic et al. provide an overview of VR training content development, proposing a structured algorithm for designing and implementing virtual training environments. Their approach emphasizes task decomposition, the use of 360° recording for capturing real-world processes and iterative design to ensure the effectiveness of the training content (Marjanovic et al., 2018). Following this approach, Huerta et al. developed an AR/VR application for engineering education, suggesting that combining multiple teaching approaches such as animations, simulations and text-based methods, can significantly enhance students' understanding of technical subjects. They further present a structured process for animation development, outline the required hardware and software infrastructure and emphasize the importance of interactivity in improving the overall learning experience (Huerta et al., 2019).

Therefore, this paper establishes a structured theoretical framework and demonstrates its practical implementation through the development of a VR training application, specifically for the CreatBot™ D600 Pro 3D printer. The proposed system is designed to provide users with direct, printer-specif-

ic training, while also addressing the broader stages and principles of the 3D printing process. By combining a structured theoretical framework with a practical immersive application, the study contributes both a methodological basis and an applied training environment for further exploring the potential of immersive virtual laboratories in 3D printing education.

In addition to the design of the virtual environment, the selection of VR hardware and the game engine play a critical role in shaping the overall user experience. In this context, the Meta Quest™ 2 device and the Unity™ game engine were employed in the present research for the development of the application. Defining these technologies from the outset and considering their technical characteristics and inherent limitations is essential, as they influence the design capabilities, graphical quality, system performance and user comfort. Consequently, optimizing the application in accordance with the selected equipment is crucial for minimizing user discomfort including motion sickness and dizziness.

Proposed methodology

For the purposes of this study, a VR application was developed with the learning objective of training users in the 3D printing process, and more specifically with the operation of the CreatBot™ D600 Pro. Based on these objectives, a series of training and educational activities was developed, with the expected outcome of preparing users to apply the acquired knowledge when operating with the physical CreatBot™ D600 Pro printer.

Figure 1 presents the proposed workflow used to develop the VR experience. The process is divided into four main phases, providing a structured overview of the methodology. The exploration phase involves a review of the state of the art, focusing on the fields of virtual reality and 3D printing in education. It aims to investigate existing technologies, teaching methodologies and instructional approaches while identifying the current challenges and limitations. This process provides a solid foundation for defining the main objectives and overall purpose of the proposed training environment, aiming for a complete 3D printing teaching course. The following two phases, namely the digital roadmap and the implementation, correspond to the development of the VR application itself. These phases are responsible for structuring the system design and implementing the core functionality, in alignment with its main objectives. Lastly, the early evaluation phase provides a preliminary and exploratory assessment of the proposed digital training environment. It is necessary for evaluating its effectiveness among users, while the collected data is used to support further refinement and improvement of the system.

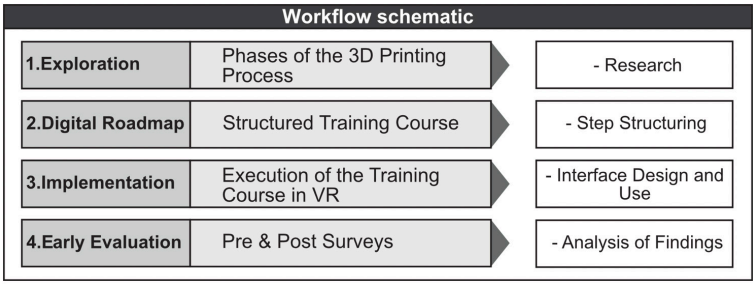


Fig. 1. Workflow schematic

Development

This section provides a more analytical explanation of the main categories presented in Figure 1, examining each of them and justifying their purpose within the proposed framework.

Exploration: The main objective of the exploration phase is to conduct a focused investigation of the domains. In the context of 3D printing, additional data were gathered, regarding the entire Fused Filament Fabrication (FFF) process, including its sequential steps, the required tools/software and educational approaches reported in existing studies. Similarly, in the field of VR, an analysis was performed to identify existing applications, their employed methodologies and their outcomes, along with the different approaches adopted across studies and the techniques used for implementing the training in virtual environments. Additionally, key aspects related to VR design were further examined, including the importance of multisensory processing, the use of multimedia, usability considerations and the integration of guiding instructions to enhance the user experience.

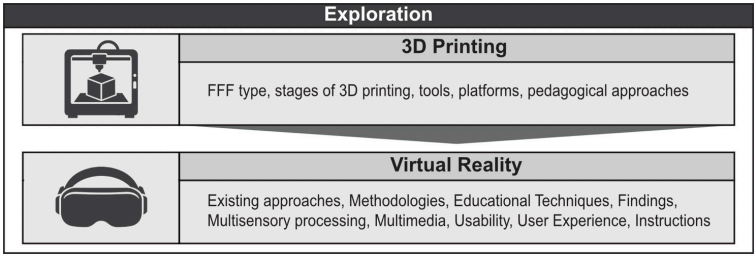


Fig. 2. Exploration categories

Digital Roadmap: In continuation of the research context, the digital roadmap phase organizes the core concepts and ideas of the application and systematically maps them onto designated points within the VR environment, to guide users through the established learning pathway. The roadmap is designed to include both introductory and advanced learning, while also recommending and presenting the required tools.

Accordingly, the designed concept is divided into sections based on the objective and the level of difficulty. Figure 3 illustrates a detailed representation of the educational application concept, organizing it into the following key steps. At the introductory learning stage, fundamental topics such as the historical evolution of 3D printing, the theoretical background of modeling and slicing software, and an introduction to key operational parameters, are presented through the integration of multimedia learning strategies in VR. At the advanced level of learning, where more complex subjects are presented, such as the evaluation of the process and the most common malfunctions, it is required to employ different and more optimized learning strategies. Therefore, the strategies of presenting these categories are focused on cognitive load management principles, where it makes it easier for students to segment complex information. Correspondingly, as the users begin to understand and gain experience during the virtual 3D printing training, they are introduced to the recommended tools for creating 3D models and generating their G-code accordingly. In the final stage, VR technology is used to its full potential, where simulations of the entire process are presented. Activities such as layer visualization and complete printer operation are implemented, enabling users to interact and experience the process in an immersive way.

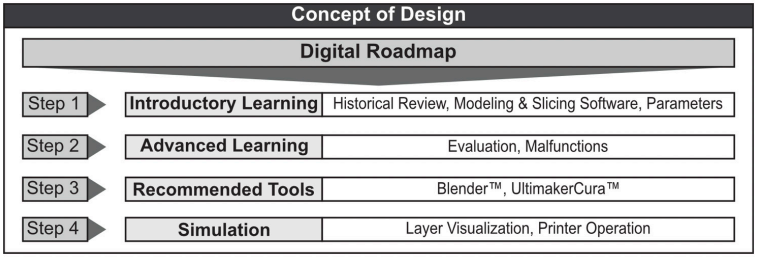


Fig. 3. Digital roadmap of concept design

Implementation: The implementation phase focuses on the development of the proposed 3D printing training environment, where the defined concepts and structures are transformed into an interactive VR environment.

This process utilizes the capabilities of VR, which are strategically aligned with cognitive load considerations and learning objectives, to enhance the overall effectiveness of the training experience. Based on Figure 4, the techniques and capabilities of VR are adapted to correspond with each learning stage.

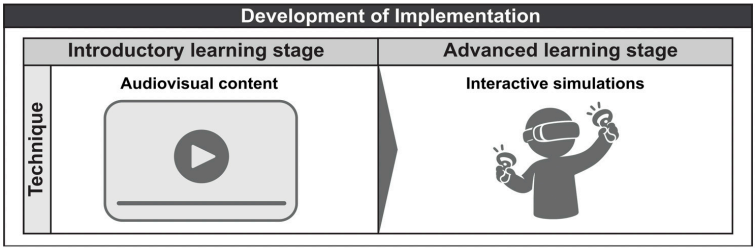


Fig. 4. Techniques used in the implementation phase

More specifically, the introductory learning stage, which presents the foundational concepts of 3D printing, is delivered with the use of audiovisual content, primarily in the form of videos, as it mainly consists of theoretical information. Building upon this, further attention was given to the proper design and effective use of educational videos. To maintain users' attention, the videos were kept short and simple, text-heavy presentations were minimized, narration was provided for each slide, and subtle background music was added. Furthermore, at advanced learning stages, where users are familiar with the virtual training environment and the learning subject of 3D printing, teaching techniques shift toward deeper understanding and cognitive optimization. As the activities involve more complex information, approaches that enable multisensory processing and active user engagement such as interactive simulation-based techniques are incorporated.

In more detail, an exhibition stand was created to showcase common 3D printing malfunctions. The stand features realistic 3D models representing each defect, along with corresponding titles and interactive elements that provide additional information and explanation of possible causes. In this way, users can freely explore the exhibition of real-world malfunctions and examine each defect from multiple angles, thereby facilitating better understanding, while supporting cognitive load management.

Likewise, a dedicated area within the training grounds was established to present layer visualization based on the predefined G-code files. More specifically, this interactive area features a set of objects linked to their corresponding G-code, allowing users to engage with them and observe their

sliced geometry and printing simulation. The aim of this activity is to allow users to explore the relationship between the object and the G-code instructions, while enhancing the visualization of otherwise hidden processes, such as the layer's formation of the sliced geometries. Thereby, this approach encourages exploratory learning as users can easily recognize and distinguish different layer components, such as infill, support, skin, skirt, walls and travel lines. Furthermore, it encourages users to explore and visualize the toolpaths at their own pace.

Finally, at the advanced learning stage the final activity is a simulation of the complete 3D printing process, which constitutes the final and most critical part of the application. At this stage, users are required to apply the knowledge introduced in the previous phases through direct interaction with the system. More specifically, the simulation is based on the CreatBot™ D600 Pro printer, and it is integrated into the VR environment to replicate the real-world printing workflow.

The purpose of this activity is to support experiential learning, by providing users with an immersive hands-on training experience. To ensure realism, the complete printing workflow was documented and decomposed into interactive sequential steps. Throughout the activity, users are required to physically perform actions such as inserting a virtual USB device to transfer G-code to the 3D printer, loading the appropriate filament into the extruder, and navigating the printer interface to initiate the heating process and start the printing process. Additionally, the warm-up phase is simulated through visual feedback, allowing users to understand the preparation requirements before fabrication begins. Therefore, the fabrication process is visualized at realistic scale and with an accelerated time progression, illustrating layer-by-layer material deposition.

To ensure accurate simulation, key specifications such as the dimensions, internal components and technical characteristics of the selected printer were considered and modeled using Blender™. Particular emphasis was placed on accurately recreating the original system, as dimensional accuracy is essential for recreating a realistic representation of both the printer and the printing process. As illustrated in Figure 5, each image is presented in a comparative format, with one half displayed in grey to illustrate the base geometry, while the other half is rendered with realistic materials and textures, representing the final visual outcome of the CreatBot™ D600 Pro printer.

By integrating the aforementioned approaches, VR offers a comprehensive training environment that supports both theoretical knowledge acquisition and practical skill development. Specifically, the combination of visualization, interaction and simulation aligns the learning subject with the users'

needs, in a more meaningful and experiential manner. Consequently, this approach is intended to facilitate a deeper understanding of the 3D printing workflow, which is otherwise difficult to achieve through traditional teaching methods.

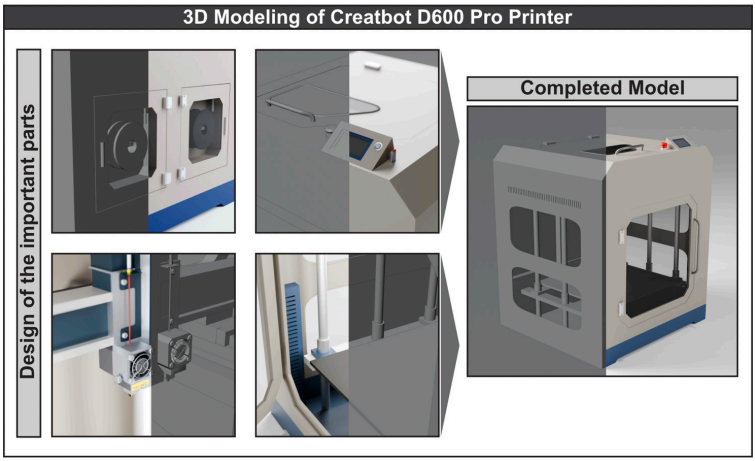


Fig. 5. 3D Modeling of CreatBot™ D600 Pro Printer.

Early Evaluation

A preliminary evaluation was carried out involving 10 undergraduate students from the field of Product Design. Given the limited sample size, the evaluation was exploratory in nature, and the findings are interpreted as preliminary and exploratory. All participants provided informed consent and confirmed their eligibility to interact with the VR environment. The participants had little or no previous experience with VR technologies. Each evaluation session lasted approximately 25 minutes and was conducted with the users seated, in the same indoor environment. During the evaluation sessions, participants' interactions with the VR environment were systematically observed and monitored.

The aim of this evaluation was to examine users' perceptions of the structure, coherence and educational potential of the designed course. Participants completed questionnaires developed specifically for this study, both before and after interacting with the VR application. The questionnaires were used to compare participants' perceptions and self-reported familiarity with 3D printing before and after the VR experience, as well as to collect feedback regarding the design and educational content of the application.

Tables 1 and 2 present the results of the pre- and post-interaction questionnaires, using a five-point Likert scale, ranging from 1 (strongly disagree) to 5 (strongly agree), together with the measures of response variability.

As shown in Table 1, prior to interacting with the application, participants already expressed a positive perception of the potential contribution of educational VR applications to learning, with a mean score of 4.7 and responses ranging from 3 to 5, while after interaction it increased to 4.8/5, with a response range narrowed to 4–5. Furthermore, regarding participants' prior familiarity with the basic steps of the 3D printing process, their mean score was 2.7 which increased to 4.7 after the use of the virtual training environment, while the observed responses shifted from a wider range of 1–3 in the pre-questionnaire to a narrower range of 4–5 in the post-questionnaire.

Table 1. Pre- and Post-VR Experience Questionnaire Results.

Questions	Pre-questionnaire	Post-questionnaire
Educational VR applications contribute positively to learning.	4.7	4.8
I am familiar with the basic steps of the 3D printing process.	2.7	4.7

Additionally, Table 2 presents the responses to the questions administered only after interaction with the VR application. The design of the application and the techniques implemented to support 3D printing education were highly rated, achieving a mean score of 4.8 with responses ranging from 4 to 5. Similarly, participants reported a high level of satisfaction with the knowledge they perceived to have gained through the application, with an identical mean score of 4.8 and an observed range of 4–5.

Table 2. Post-VR Experience Questionnaire Results.

Questions	Post-questionnaire
The design and integration of the educational resources supported my understanding of the basic functionality of 3D printing.	4.8
I am satisfied with the knowledge I gained from the educational application.	4.8

Following the questionnaires, a practical task was conducted using the CreatBot™ 3D Pro printer. Each participant was required to complete three printing specimens in accordance with the VR experience. The difficulty of the specimens increased progressively from easy to intermediate and advanced. Their performance was evaluated according to whether each printing task was completed successfully or unsuccessfully.

As presented in Table 3, all 10 participants successfully completed the easy task, 8 out of 10 successfully completed the intermediate task, and 6 out of 10 successfully completed the advanced task. The results show a progressive decrease in the total number of successes. Nevertheless, it confirms that more than half of the participants successfully completed all three levels of the 3D printing task. Therefore, the practical assessment provides objective validation that the VR application helped participants apply the knowledge and procedures in a real-world 3D printing task.

Table 3. Post-VR Practical Task Results.

Task	Total number of
3D printing of an easy	10/10
3D printing of	8/10
3D printing of	6/10

Conclusions

This study proposes a four-phase theoretical framework for learning the FFF 3D printing process using the CreatBot™ D600 Pro through a comprehensive VR-based training environment. The proposed approach combines theoretical and practical elements of 3D printing education within an immersive environment, leveraging the capabilities of VR in alignment with the defined learning objectives. The process includes introductory theoretical knowledge as well as practical skill development, such as slicing, layer recognition, identification of common printing malfunctions and simulation of the overall printing operation. These elements are organized into a digital learning roadmap designed to guide users through the training process, starting from introductory stages and progressing to advanced levels.

A preliminary and exploratory evaluation involving 10 undergraduate Product Design students provided encouraging results regarding both users' perceptions of the developed application and their performance in the post-VR practical assessment. Participants evaluated the design and educational content positively and reported greater familiarity with the basic stages of

the 3D printing process. In addition, the practical assessment demonstrated successful task completion, with the majority of the participants progressing through all three levels of the 3D printing task. These findings provide preliminary evidence that participants were able to apply the knowledge and procedures from the VR training to a physical 3D printing environment.

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