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The Use of Virtual Reality in Manufacturing Education: State-of-the-Art and Future Directions

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Abstract

Innovative technologies such as virtual reality and additive manufacturing have been drastically changing our society, from how we design and manufacture products to how to educate and train the next-generation workforce. This paper reviews scientific studies on virtual reality assisted manufacturing education published from 2015 to 2022 from three different perspectives: targeted manufacturing disciplines/topics, virtual environment development, and outcome evaluation methods. This paper also summarizes the critical limitations of existing studies and identifies the key challenges in the field. Furthermore, some future research directions are discussed aiming to advance current manufacturing education and deliver a highly skilled workforce for U.S. future manufacturing.

Keywords: Manufacturing education; Virtual reality; Virtual training; Experiential learning

1. Introduction

In Jan. 2021, President Biden signed an executive order entitled "Ensuring the Future is Made in America, by Americans - All of American Workers", as the first step toward the Build Back Better Recovery Plan [1], which shows the White House's commitment to strengthening American manufacturing. The U.S. manufacturing industry generates $2.33 trillion, which accounts for 11.39% of the total output of the national economy; An average of 12.8 million people are employed in the manufacturing industry, which is 8.51% of the U.S. workforce in 2018 [2]. In recent years, innovative manufacturing technologies (e.g., additive manufacturing), materials (e.g., composites, stimuli-responsive materials), design methodologies (e.g., biomimicry), and modeling/control algorithms (e.g., the use of artificial intelligence) have been introduced to the manufacturing industry, resulting in new challenges as well as opportunities for manufacturing education and workforce development. Examples of these challenges include the high capital investment of some new manufacturing processes/machines and the high risks for the environment and for human health posed by some devices and materials used in advanced manufacturing, such as high-power laser and ultrafine particle materials.

To address the above challenges introduced by new manufacturing technologies, effective workforce training on some new knowledge and skills is required in manufacturing education and industry. To achieve this goal and enhance the readiness of the future manufacturing workforce, the manufacturing industries have been searching for new, efficient training methodologies to replace/complement traditional experiment-based training [3]. In recent years, virtual reality (VR) technologies have been leveraged in the manufacturing industry for training. The prominent U.S. automaker Ford introduced VR in employee training for design and production in 1999. Now, an estimated 33% of U.S. manufacturing industries are utilizing VR technology to boost productivity. The worldwide pandemic has accelerated its acceptance, and more intensive adaption of VR is on the way in the near future. The leading manufacturing industries such as Ford, General Electronics (GE), and Lockheed Martin aerospace and defense companies have successfully incorporated VR or/and augmented reality (AR) technologies in workforce training and production. In return, they found tremendous productivity improvement. Ford has its VR specialist team for training the engineers to design and fabricate the complete vehicle in the VR environment. Even Ford implemented multifunctional VR to scrutinize the vehicle before sending them to the production line. Ford found VR a time-efficient, cost-effective employee training procedure that significantly improves production quality. VR is also found to be explored in maintenance and assembly training. GE performed a productivity study on wiring the wind turbine in the virtual environment. They developed a smart glass that guides the engineers' showing videos, audio, and floating text instructions to wire a complete wind turbine. A 34.5% productivity improvement was revealed compared to the traditional wiring training [4]. Lockheed Martin developed a virtual environment to train the workforce to build the F-35 fighter plane. They reported that the employee who received the VR training worked faster with 96% accuracy during real-world fabrication. These findings suggest that VR could be an extremely value tool in the education and training of next-generation manufacturing workforce.

Prior research has shown that trainees usually lose interest in stable, non-interactive, and unengaging lectures and therefore miss crucial information, which may cause a significant negative impact on the quality and quantity of graduates in applied fields like manufacturing. Therefore, in manufacturing education, engaging students in the learning process and hands-on experience is of urgent need to society. In the last decade, numerous attempts have been dedicated to improving teaching methods in manufacturing or engineering in general, through the course material modification, the use of new techniques, technology-driven platforms, and even replacing traditional lectures with evidence-based applied learning or project-based learning. Among these new attempts, technology plays an increasingly critical role because it can transform a passive, reactive education system to become interactive and even an enthusiastic one. Different technologies can be incorporated as a part of the curriculum, an instructional delivery system, a means of supporting instruction, an instrument to enhance the learning process, and/or a tool to evaluate and improve teaching. However, despite the availability of new technologies, most teachers have been slow to transform the ways they teach. It is crucial to ensure that the new technology-based platform can easily be adapted by course instructors in diverse fields and to support customized course requirements.

Immersive training platforms like VR and AR have been proven to be effective for student learning and workforce training in many educational and industrial settings [5]–[7]. VR is particularly useful for training that involves high-risk work environments and/or complex operating systems where students lack access to high-tech expensive equipment or have restricted access, especially for students with disabilities. VR allows access to activities that may not be possible to experience by students with physical disabilities or partial hearing or visual disabilities. For example, using gaze-based interaction, students do not need to use their hands to operate controllers while interacting with virtual environments, and depending on which course materials they want to focus on, any audible alerts can be amplified, or color blindness can be corrected.

Considering the unique challenges posed by education and workforce development in the manufacturing industry, especially in future advanced manufacturing, training in VR may be a promising solution. VR provides students with a fully immersive and highly interactive learning environment where they can explore different virtual objects through visualization added with immediate feedback and assistance. Students can actively use trial and error to practice assigned tasks and evaluate their learning experiences without further observation and assistance from the instructors. The most useful feature of the VR learning environment is its efficient student evaluation process with time-series data on many performances and interaction measures including error rates, task completion time, number of trials needed, and time spent on each course content and tasks among many others.

In the literature, many review articles have been published on VR, and they mostly focus on the technologies [8] or the general application [9], [10]. Only a limited number of literature review papers are focused on the application of VR in the manufacturing industry. For example, a review article was published in 2015 by Choi et al. [11] that covered research efforts on VR's application in the manufacturing industry until 2014. A systematic review of VR applications in higher education was published in 2020 [12], and it only reviewed one research article on manufacturing education [13]. Another comprehensive review on VR as a pedagogical tool in education was published by Hamilton et al. in 2021 [14], and it only reviewed one paper on manufacturing education [15]. The current literature indicates a need for a more focused, in-depth review of the use of VR techniques in manufacturing education with identified future research directions. Hence, this paper will focus on the scientific articles published from 2015 to 2022 on the topic of VR applications in manufacturing education.

2. Methodology

The research articles reviewed in this paper were searched from Google Scholar using keywords such as "virtual training manufacturing education," "virtual reality manufacturing education," etc. The time frame was set to be from 2015 to 2022. A total number of 13 scientific articles are reviewed in this paper, and they are published in journals such as *Sustainability*, *Journal of Mechanical Design*, and *Research in Engineering Design*, and conferences such as *International Conference on Virtual and Augmented Reality in Education* and *International Conference on Foundations of Digital*

Games. A summary of the reviewed articles is shown in Table 1.

Note that the current literature shows that VR has been used in the manufacturing industry for many purposes such as product design, assembly/production line simulation, human-robot collaboration, and process planning, etc. [3], [16]–[18]. Since these papers are not focused on manufacturing education, they are not reviewed in this paper.

3. The State-of-the-Art Review

The collected 13 papers on VR-assisted manufacturing education are reviewed in detail from three aspects: targeted manufacturing knowledge and skills, the VR environment development, and the evaluation methods.

3.1. Targeted Manufacturing Knowledge and Skills

Among the reviewed articles, a few areas of manufacturing knowledge/skills are identified: automobile manufacturing, manufacturing design, manufacturing sustainability, and additive manufacturing. The majority of these studies are focused on the education of introductory knowledge and basic operation.

Automobile manufacturing, as one of the more traditional manufacturing industries, is facing critical challenges in terms of sustainability, flexibility, ramp-up, and time-to-market shortening. This requires operators to have access to effective, efficient training on hardware in the production lines/systems. Ordaz et al. (2015) developed rigorous games and a virtual simulator that is embedded with a range of educational scenes including loading a robotic welding machine and manual welding on a rotary fixture [19], as shown in Figure 1. The entire training process is divided into 18 steps with three difficulty levels (easy, medium, and expert). This study shows that the designed virtual training has a high potential and acceptance level to be integrated into industries. Results also indicate that the “user’s game experience” does not seem to change the way the users recall the order of the assembly, but it does change the completion time. *Welding* is a critical skill to the manufacturing workforce, not only in automobile manufacturing but also in many other manufacturing processes. VR has become increasingly popular in educating and training welders in the industry due to the high cost and environmental impact of extensive hands-on welding training. Price et al. (2019) used a VR system for the purpose of introducing entry-level industrial distribution undergraduate students to welding processes better to prepare them for hands-on welding in

Table 1. A summary of reviewed articles

No.	Ref.	Year	Topics in Manufacturing	VR Development	Learning Outcome Evaluation
1	[19]	2015	Automotive manufacturing education (welding nuts, loading a robotic welding machine, manual welding, etc.)	The Virtual Simulation and Training Simulator (VTS)	Completion time and number of errors are used to evaluate the usability of the virtual training
2	[27]	2016	Enhance students’ interest and awareness of manufacturing through game-based learning	Cave automatic virtual environment for interactive product assembly use case	Structured questionnaires for before and after intervention, and long-term evaluation are used for evaluation
3	[29]	2017	Virtual Reality game-based interfaces for manufacturing	Virtual building system in Unity	The usability is evaluated using pre and post questionnaires.
4	[15]	2018	Introductory concepts in additive manufacturing	An VR environment with a Fused Deposition Modeling 3D printer	Pre- and post-test scores and ANOVA analysis of the difference between VR and physical training
5	[20]	2019	Welding education	A virtual simulator to improve manufacturing process education	Pre and post welding questionnaires are designed to evaluate the efficacy of the VR environment.
6	[21]	2019	VR environment of a machine valve system assembly	Application of VR technology in industrial and manufacturing engineering	VR performance is assessed based failure modes and effects analysis
7	[24]	2019	Manufacturing sustainability in industry 4.0 and reconfigurable manufacturing systems	The shop-floor environment	The efficacy of the VR training is evaluated through a brief statistical analysis on completion time and number of errors
8	[23]	2019	Manufacturing design education	Interactive, immersive VR technologies developed in Unity game engine	Eye tracking data will be analyzed to determine the students’ engagement
9	[25]	2020	Manufacturing sustainability in industry 4.0 (case study: water treatment	Virtual environmental chemistry lab	Questionnaire with closed and open questions
10	[26]	2020	Introductory concepts in additive manufacturing	FDM 3D printing system	The VR training efficiency is evaluated using pre and post questionnaires, and statistical analysis (a two-way mixed analysis of variance ANOVA) on process time
11	[30]	2021	Safety training in chemical manufacturing	Virtual chemical manufacturing environment	VR is assessed using survey and interviews of the participants and statistical analysis
12	[22]	2022	Manufacturing Education 4.0	Biomechanics robotic interface	Continuous formative assessment was demonstrated through live-access multi-streaming of design applications
13	[31]	2022	Additive manufacturing education	Virtual environment for design a 3D printable shop dish	The performance is evaluated using pre and post designed based on AM concepts which covers print orientation

engineering labs [20], covering both the gas metal arc welding (GMAW) and shielded metal arc welding (SMAW).

Figure 1. The manual welding scene in the virtual environment [19]

Manufacturing design is another area that has leveraged the use of VR in education and training. For example, cognitive design review, FMEA (failure modes and effects analysis), and criticality analysis (CA) during the design of new customer-specific products are covered in the VR training studied by Bellalouna (2019) [21]. In addition, Kleppe and Bjelland (2022) developed a range of virtual concurrent engineering tools to enable multi-site teaching, learning, and social interactions in engineering disciplines including manufacturing design [22]. Zhao et al. (2019) developed a VR simulation game for educating undergraduate engineering students on solving design and manufacturing problems and utilizing professional skills to improve their performance and outcome [23].

Public awareness and literacy on sustainability issues faced by our society in general and *manufacturing sustainability* have been drastically increasing. To drive the future manufacturing industry towards much-enhanced sustainability and circular economy, critical knowledge and skills are required in waste management, energy efficiency enhancement, environmental impact evaluation, cost analysis, and optimization, etc. In the literature, research attempts have been conducted to leverage VR in facilitating the education and training of manufacturing sustainability. Salah et al. (2019) developed a VR tool (shown in Figure 2) to train and educate young students in product manufacturing with targeted concepts in Industry 4.0 and reconfiguration manufacturing systems (RMS) and a case study on designing a machine vice assembly [24]. Krupnova et al. (2020) examined the use of the virtual learning environment as an experimental approach to conduct manufacturing sustainability education (with a focus on environmental education) [25]. A virtual environmental chemistry lab was established to conduct the case studies. Results suggest that students have predominately positive feedback and confirm the benefits of using VR in the educational context.

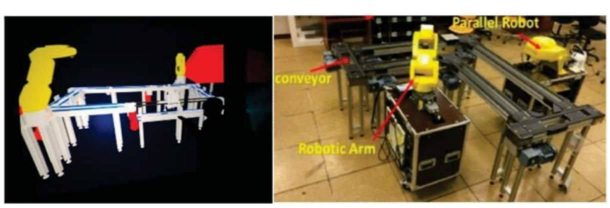

Figure 2. The RMS in (left) VR and (right) physical environments [24]

In recent years, novel manufacturing processes/technologies such as *additive manufacturing* (AM) have received increasing public interest owing to the faster production speed, increased manufacturing complexity, and enhanced manufacturing sustainability ensured by the unique layer-by-layer production method. With the numerous innovations and advancements in AM technologies in both hardware and software, some industries have started the early-stage implementation of AM, such as automobile and aerospace, indicating a growing demand for a highly skilled workforce in the field of AM. Ostrander et al. (2018) developed a VR environment of the Fused Deposition Modeling (FDM) AM process, as shown in Figure 3, to help students gain an understanding of introductory concepts in FDM, including build time, layer-by-layer deposition, material use, support generation, build orientation, Cartesian coordinates, extruder components and functions, and hot end components and functions [15], [26].

Other research efforts on VR-based manufacturing education have been conducted. For example, to attract young students and increase their awareness and interest in manufacturing, Stratos et al. (2016) used an immersive VR simulation of a manual assembly task [27]. The results show that the VR-based knowledge delivery mechanism can positively impact the students and promote awareness of manufacturing among young students.

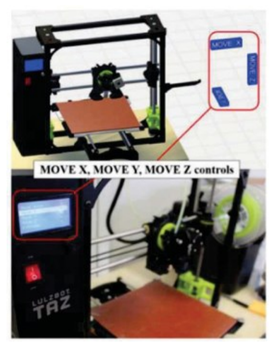

Figure 3. The FDM printer in (up) VR and (bottom) physical environments [15], [26]

3.2. The VR Environment Development

VR developers use different approaches to create partially immersive environments, such as desktop simulation and projector-surrounded space, and fully immersive environments, such as 3D environments experienced with head-mounted displays. Partial immersive environments can be created using different simulation software and presented on single or multiple TV or projector screens. When multiple projector screens are used as walls to create a virtual room environment, this is called the Cave Automatic Virtual Environment (CAVE). In partial immersive environments, users interact with virtual components using a mouse, joystick, button press, or sometimes with verbal responses. The user's navigation and interactions can be tracked for assessment using motion sensors or optical tracking sensors. Visual, audible, and haptic cues are designed within the simulated environments to provide feedback to users.

There have been several studies that have developed different VR approaches to create partially immersive training environments. In one research study, Ordaz et al. (2015) used a TV screen to present virtual assembly line operations to train and test students on assembly processes [19]. Trainees utilized a Nintendo WiiMote controller to manipulate virtual components with a button press. The Microsoft Kinect tracked users' body positions and postures within the virtual environment to record their navigation and interaction within the virtual world. For a similar training purpose, Stratos et al. (2016) used a three projector-surrounded CAVE [27] where learners used VR glasses to get an immersive experience and navigated inside the virtual environment using a virtual hand controlled by the human hand. Users' interactions were tracked with optical tracking of their head and right-hand positions. Another study used a similar approach to create a semi-immersive operation suite in a virtual machine shop [28]. Krupnova et al. (2020) developed a desktop simulation to create a virtual chemical lab environment for studying air pollution, water and wastewater treatment technologies and risk assessment.

Figure 4. Virtual environments presented in TV (left) and projector (right) screens [19], [27]

While these partially immersive environments can enhance trainees' learning experiences with reduced expense, greater safety, and less environmental impact, they sometimes lack the urgency and risks of real-world manufacturing settings. Fully immersive virtual environments can address this gap by completely separating users from the real world. These realistic environments can be developed using game engines which provide VR developers with the necessary framework and resources. Academic VR developers mostly use Unity3D with mobile device platforms while professional VR developers use Unreal Engine which is more suitable for desktop computer platforms. In these virtual environments, users can utilize VR controllers as well as their gaze to interact with virtual objects.

Figure 5. The fully immersive environment experienced with virtual reality headsets [21]

When head-mounted-displays became commercially available, Dinis et al. (2017) used Unity 3D to develop virtual learning environments and trained students to build factory models [29]. This fully immersive environment allowed learners free walkability and tracked users' interactions using game controller units and motion sensors. Ostrander et al. developed an introductory additive manufacturing training program using Unity, immersed trainees with HTC Vive headsets, and allowed them to manipulate virtual objects with Vive controllers [15], [26]. This learning platform consisted of high-quality graphics and base stations to track the headset and controller positions. The studies compared traditional and virtual learning approaches and found VR to be effective for additive manufacturing training. In another study, Price et al. (2019) utilized a welding hood and replaced eyepieces with VR glasses to enable learners' visualization of virtual welding settings [20]. Instructors were able to observe the scenarios visualized by the trainees and provided them feedback for corrective actions. Using a similar VR development and tracking approach, Bellalouna (2019) created a user-friendly and intuitive virtual machine shop environment to train students about risk analysis [21]. The successful immersion into this learning environment confirmed the enhancement of users' cognitive decision-making and critical-thinking skills through virtual training.

In 2019, Zhao et al. used a more advanced approach to develop a VR simulation game for assembly operations using Unity and an HTC Vive Pro Eye headset [23]. Users' eye-tracking data was used to develop an Artificial Intelligence (AI) assistance to design the content and timeliness of virtual instructions within the virtual learning platform. In a recent study, Poyade et al. (2021) developed a chemical manufacturing lab for safety training [30] using this approach. The training environment provided students with a virtual tablet that allowed them to follow task orders and to get assistance with highlighted areas within VR for identifying areas of interest (task). In addition to AI-based assistance and realistic record-keeping with virtual tablets, Kleppe and Bjelland (2022) developed a collaborative virtual environment to allow multi-site teaching and learning [22]. These advanced methods are found to improve students' engagement in active learning and reduce their frustrations with remote online learning.

3.3 Evaluation Methods

Evaluation of efficiency, usability, and sustainability is conducted throughout studies of VR technology in manufacturing training. In general, the evaluation is applied in two different ways, 1) designed metrics to quantify training effects, 2) conducted a survey using properly designed questions to gather subjective responses from participants and analyze responses further to quantify the usage of VR technology in the training procedure. These evaluations cover the impacts of VR technology on students' education and operator training in the following perspectives, 1) existing background knowledge of VR technology infrastructure impact on training results, 2) comparison of pre-training and post-training on the tester in VR training procedures, 3) comparison of training impact on targeted VR usage group and control group.

Among these four major categories of evaluation methods, the first step is to *properly define and quantify the training* *effects*. Ordaz *et al.* (2015) proposed metrics of completion training time and mistakes count at various training difficulty levels to measure training effectiveness [19]. Collected metrics were then used further to establish a comparison between users with and without gaming experience to evaluate the pre-existed familiarity with technology infrastructure impacts on training results. To examine VR-based FMEA and CA applications, Bellalouna *et al.* (2019) collected data from operators without awareness of the existing VR objects under the same given work instruction at different areas and proposed criticality factor K to provide design countermeasures with the target of ensuring machine safety [21]. Zhao *et al*. (2019) used participants' time consumption at different stages of the complete workflow to evaluate the effectiveness of VR training [23]. Furthermore, Zhao *et al.* (2019) proposed a player modeling approach to leverage user interactivity in VR training. Salah *et al.* (2019) used metrics of completion time, error amount, and percentage of completion to evaluate training performance [24]. With collected metrics, the comparison between the group using the VR training process and the control group without using the VR training process was conducted. The comparison shows that the experimental group completed configuration tasks consuming less time and a smaller number of errors than the control group. A two-sample t-test was selected to compare the performance data from the experimental group and control group with a normality check (Anderson-Darling).

For the categories that cannot easily be quantified by objective observation, such as tester subjective experience, and infrastructure usability from the tester perspective, a *survey* has been widely and commonly used by researchers. After the survey, further data analysis on be applied to responses collected from participants to reveal valuable information from different perspectives. Ordaz *et al* (2015) conducted a survey after training to evaluate usability, covering various aspects of experience including fidelity to reality, tool handling, contribution to the learning process, assembly sequence understanding, and ergonomics [19]. Price *et al* (2019) conducted a Qualtrics survey to assess the student's responses using a Likert scale. The questions cover impressions of students before and after using the VR welding system, self-assessment on confidence to wield safely after VR training, and overall assessment of wielding ability after VR training [20]. Bellalouna *et al.* (2019) collected user feedback on VR experience, usability and learnability, and interactivity [21]. Salah *et al.* (2019) designed a survey and distributed it during the examination period to a sample of the course participants to allow participants to self-evaluate on scale of score. The survey covered aspects of course organization, methodology, supervisors, and acquired skills [24]. Krupnova *et al*. (2020) designed the survey with both open and closed-ended questions with the purpose of gaining the participants' feedback on advantage and disadvantages of VR technology usage in higher education [25]. The survey was distributed among undergraduate students studying environmental technologies at the South Ural State University.

Different from the previous one-time-only survey approach, *a series of surveys* conducted at multiple stages of experiments were designed to show the impact of VR-involved training procedure impact throughout time, as well as in the long term. Ostrander *et al*. (2019) explored the usage of VR training in additive manufacturing and proposed metrics evaluating multiple perspectives, including additive manufacturing self-efficacy both from functions and design for additive manufacturing and additive manufacturing conceptual understanding [26]. The responses of participants were collected from pre-lesson and post-lesson. Numerous comparisons of responses from the experimental group (trained with VR technology) and control group (trained without VR technology) were conducted, as well as static analysis. For example, learning differences between two groups were examined using a two-way mixed analysis of variance for each of the eight pre-identified AM concepts. Similarly, Stratos *et al*. (2016) conducted a series of surveys as assessments of the participants at different stages of the experiment to evaluate the effectiveness of the VR training procedure [27]. Questions in the survey were designed with a focus on students' interests and awareness towards manufacturing as a learning domain, as well as the potential career path of a manufacturing engineer. The assessments were conducted pre-VR application training, post-VR application training, and 2-3 weeks after VR application training as an evaluation of long-term effects. During the assessments, pedagogically acceptable, well-established monitoring mechanisms were employed to monitor participants. From collected responses, the level of interest and level of awareness change were studied and summarized.

Considering pre-existed knowledge of VR infrastructure's impact on training results, a comparison between participants with considering of their background knowledge is also conducted. Dinish *et al*. (2017) conducted a survey to assess the usability and intuitiveness of the commands received by participants during interacting with a virtual environment to build models using a VR interface [29]. Responses were collected on a Likert scale and analyzed. The data was structured into two major groups based on their academic background. In each group, the participants were split into 2 more sub-groups based on their previous experience with VR, e.g., with VR experience group and without VR experience group. Besides, using VR to explore building solutions was also studied. The survey targeting on participants' existing knowledge of the building system and VR experience and changes in the ability to identify examples of the buildings were also conducted after the VR trial. Furthermore, a third use case was studied to discover the main disciplines involved in a civil engineering project using VR. All participants were survived about their previous experiences with VR equipment, along with a Likert scale evaluating the effectiveness of VR experience on information transfer. Poyade *et al*. (2021) designed a standardized survey on both of experimental group (trained with VR technology) and the control group (trained without VR technology), which covers major perspectives of task-specific learning effect, perception of learning confidence, sense of perceived presence, usability, and sentiment analysis [30]. For comparison between the experimental group and control group across the perspectives of task-specific learning, perceived learning confidence, and presence, a series of Mann-Whitney U tests were conducted using PSPP. On top of responses that can be quantified from previous perspectives, sentiment analysis was also included and conducted to assess consistency between statistical analysis and received verbal responses in texts. Specifically, verbal responses from both groups were analyzed against the Linguistic Inquiry and Word Count (LIWC) default dictionary with a percentage of words fitting psychological descriptors so that the positive and negative emotions from participants can be captured for further analysis.

4. Conclusion

The research on VR assisted manufacturing education is an important and emerging topic which has not been given enough attention. Over past few years, the VR technology has been emerged remarkably to allow high quality graphics, greater sense of immersion, and enhanced experience of complex but flexible interactions. The review presented in this paper is mostly focused on user satisfaction and student learning. Researchers should be careful to identify new issues that may arise from the instructor-less nature of this platform including students not being able to ask for feedback and assistance to clarify any confusions. Future research should also consider instructor's acceptance of VR platform and their ability to successfully implement VR training modules. Their acceptance and accordance with the implementation of this technology in classroom teaching carries the future of this platform in workforce training.

A limitation of the review is that it includes only Google Scholar to search for relevant articles. Even though the database includes a great portion of the articles in this field, some additional articles that fit in the scope of this review may have been excluded through this search. However, the authors have tried to cover a majority of the relevant studies in this paper.

5. Discussion and Future Work

With the recent advances in VR technologies, manufacturing innovations, and education methodologies, areas that need more future research efforts are identified as follows.

- The developed VR training environment should be user friendly to both 1) new manufacturing workforce with younger generations or people who do not have game experience to a certain level, and 2) existing manufacturing workforce with older generations or people with game experience. This should be evaluated from both the effectiveness and efficiency perspectives.
- For new manufacturing processes/technologies such as metal AM and metal hybrid additive-subtractive manufacturing with high-power energy sources such as laser and powder materials, there exists potential operational safety hazards and human health risks. VR is particularly beneficial in such cases. However, VR environment development on laser-based metal AM processes has not yet been well explored.
- The developed VR environment should 1) successfully mimic real-world manufacturing lab environments, 2) allow students with high-level immersive experiences, and 3) enable them to grab and move virtual objects within VR.
- VR should track students' interaction with the virtual lab environment from heat maps developed based on their gaze behaviors and emotional expressions which can inform instructors for effective instruction and feedback designs. Haptic and proprioceptive feedback design can be effective in successful VR training.
- The virtual learning environment should be inclusive in order to address diversity in languages and issues with students' accessibility.
- Metrics and survey questions regarding the interactivity of VR technology usage in training procedures need to be designed and evaluated. Current research studies evaluate the impact of VR technology on training results. As one of the unique features brought in by VR, the interactivity of users in different scenarios for training also needs to be considered and evaluated.
- Natural language processing (NLP) technology can be introduced to process and analyze literature responses to open-end questions with expanded applications. NLP can help researchers cluster user behavior under different training scenarios and settings with further quantification.
- Similar to any emerging technologies, VR-based training may encounter acceptance issues from older and experienced workers and/or people with disabilities who cannot practice the benefits of VR. The future workforce in additive manufacturing, existing or novice, needs to accept this technology-based training and plan to use them for enhanced production and safety. Technology acceptance models and the theory of planned behavior should be applied to explore the acceptance of future workforce toward VR training.
- Researchers developing VR-based training modules need to create effective user manuals with adequate and unambiguous information for new instructors. Instructors' perceived comfort, ease of use, time to grasp knowledge, and error frequency can be useful metrics to evaluate the effective administration of VR training.

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