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Review

Immersive virtual reality application for intelligent manufacturing: Applications and art design

Yu Lei[1], **Zhi Su**[2,*], **Xiaotong He**[3] **and Chao Cheng** [3,4,*]

[1] College of Humanities and Arts, Hunan International Economics University, Changsha, 410205, China

[2] Department of Information, School of Design and Art Changsha University of Science and Technology, Changsha 410076, China

[3] Weihai Institute for Bionics, Jilin University, 264402, Weihai, China

[4] Key Laboratory of Bionic Engineering, Ministry of Education, Jilin University,130022, Changchun, China

* **Correspondence:** E-mail: 006034@csust.edu.cn; chengchao@jlu.edu.cn.

Abstract: Intelligent manufacturing (IM), sometimes referred to as smart manufacturing (SM), is the use of real-time data analysis, machine learning, and artificial intelligence (AI) in the production process to achieve the aforementioned efficiencies. Human-machine interaction technology has recently been a hot issue in smart manufacturing. The unique interactivity of virtual reality (VR) innovations makes it possible to create a virtual world and allow users to communicate with that environment, providing users with an interface to be immersed in the digital world of the smart factory. And virtual reality technology aims to stimulate the imagination and creativity of creators to the maximum extent possible for reconstructing the natural world in a virtual environment, generating new emotions, and transcending time and space in the familiar and unfamiliar virtual world. Recent years have seen a great leap in the development of intelligent manufacturing and virtual reality technologies, yet little research has been done to combine the two popular trends. To fill this gap, this paper specifically employs Preferred Reporting Items for Systematic Reviews and Meta-analysis (PRISMA) guidelines to conduct a systematic review of the applications of virtual reality in smart manufacturing. Moreover, the practical challenges and the possible future direction will also be covered.

Keywords: virtual reality; intelligent manufacturing; immersive Human-machine interaction

1. Introduction

Industrialization has now transitioned into a new phase, and all nations are propped up for the invasion of intelligent manufacturing. The major source of inspiration for a nation's machinery industry's innovation and advancement, as well as the key route for the field to change and advance, comes from smart manufacturing [1]. It is the fundamental strategy for creating a powerful nation characterized by its industry. Thousands of businesses have already adopted it [2]. Modernized manufacturing is addressing labor shortages and high labor costs, increasing production efficiency, cutting delivery times, and consuming less energy and resources, which is crucial for lowering costs, especially while enhancing product level [3,4]. In the market battle, many businesses with digital assembly lines, workplaces, and plants are in a good position.

Artificial intelligence (AI) research is the source of smart manufacturing. AI is an autonomous approach developed on a computer. The share of design as well as procedure information in the good or service has sharply increased along with the product's performance, the richness and sophistication of its structure, as well as its diversified features. Additionally, the data flow within the production equipment has also increased [5]. The data amount in the procedure and management work will inevitably increase sharply, so the hotspot and frontier of the advancement of machining have turned to enhance the capability, efficiency, and scale of the framework for the explosive growth of production data processing as is shown in Figure 1. These technologies play an increasingly important role in industry 4.0.

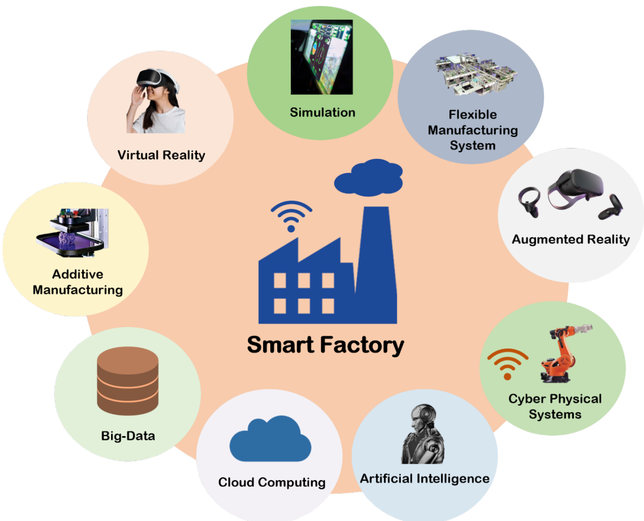

Figure 1. Application areas for smart factory, including virtual reality, additive manufacturing, big-data, cloud computing, artificial intelligence, cyber physical systems, augmented reality (AR), flexible manufacturing system, and simulation (Source: Processed by the authors)

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According to experts, industrial systems are shifting from being energy-driven to being information-driven, necessitating intelligence and flexibility because it would be challenging to manage such a heavy output of information without it [6]. Second, the complicated environment of intense rivalry and the constantly shifting market demands call for the production system to exhibit greater flexibility, mobility, and intelligence. Consequently, interest in intelligent manufacturing is growing [7]. Despite the fact that intelligent manufacturing is still in its theoretical and experimental stages globally, several governments have incorporated it into national development strategies and have actively pushed for its adoption [8]. The United States adopted a new digital strategy in 1992 and vigorously backed the president's list of key technologies, which included industry, novel manufacturing techniques, and information systems [9].

VR has developed a number of innovative displays as well as input technologies in recent years [10]. The market now offers new hardware with reasonable pricing structures. VR has made a contribution to the creation of new technologies [11]. There are emerging ideas for resolving issues with the software and hardware of current VR technologies [12]. Software and device development are at odds with the proven scientific community that has already largely implemented the newly accessible technology Mazuryk, led by hobbyists interested in the subject of virtual reality [12]. For commodity VR, equipment including haptics instruments, controllers, garments, omnidirectional simulators, tracking technologies, and visual scanners for motion interaction are much more crucial than Head- Mounted Displays (HMDs), whether they are cable-based or transportable [13].

These technologies are currently accurate and reliable enough to be used in both professional activities and scientific research. The subjects covered include frequent problems with new technologies and solutions, including motion-to-photon delay, barrel aberration, and limited displays [14]. Additional analysis of the market-targeting options is also offered. And VR will offer a taxonomy classifying recent advancements according to the selected implementation strategies [15]. This study examines the state of technical growth in this area and offers a thorough analysis of recent trends relating to prospective hardware and software updates [16].

This essay examines the state of technical growth in this area at the moment and offers a thorough analysis of recent developments about prospective hardware and software updates [17]. When used effectively, VR may help intelligent manufacturing companies make the best decisions possible, maximize product performance, enhance product quality, save costs associated with production, increase brand influence, and seize market possibilities [18].

A fundamental connection between sophisticated manufacturing technologies and production lines is now VR innovation [19]. This technology may be applied to industrial items to improve product design, minimize or eliminate the creation of simulation model through virtual assembly, accelerate development times, and save costs. Meanwhile, by creating digital factories, it is possible to make staff training, real manufacturing, and program assessment easier by graphically exhibiting factories, assembly lines, simulated examples of products, as well as the full producing procedure [20]. It facilitates communication between the necessary divisions of the company, which not only drastically cuts the period for product creation but also increases the chance for the sale and promotion of the company's products [21].

The rest of the paper is organized as follows. Section 2 presents the methodology for this review. The terminology for immersive virtual reality applications in intelligent manufacturing is provided in Section 3. Section 4 describes the recent advancements in immersive virtual reality applications for intelligent manufacturing. Section 5 discusses the state-of-the-art, current challenges, and future trends, Section 6 summarizes the paper and provides a conclusion for this review.

2. Methodology

By using Preferred Reporting Items for Systematic Reviews and Meta-analysis (PRISMA) guidelines, a systematic review of recently published literature was conducted on virtual reality applications for intelligent manufacturing. The inclusion criteria were: (i) publications indexed in the Web of Science, Scopus, and ProQuest databases; (ii) publication dates between 1990 and 2022; (iii) written in English; (iv) being a review paper or an innovative empirical study; and (v) certain search terms covered; (i) editorial materials, (ii) conference proceedings, and (iii) books were removed from the research. The Systematic Review Data Repository (SRDR), a software program for the collection, processing, and inspection of data for our systematic review, was employed. The quality of the specified scholarly sources was evaluated by using the Mixed Method Appraisal Tool. After extracting and analyzing publicly accessible papers as evidence, no institutional ethics approval was required before starting our research (Figure 2).

flow diagram describing the search results and screening.jpg

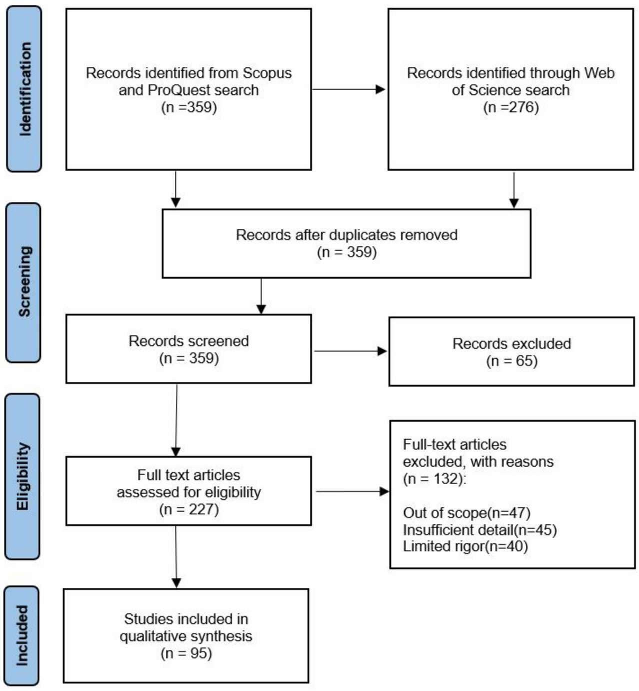

Figure 2. PRISMA flow diagram describing the search results and screening (Source: Processed by authors).

Throughout April 1990 and October 2022 (mostly in 2022), a systematic literature review of the Web of Science, ProQuest, and Scopus databases was performed, with search terms including ”virtual reality and smart manufacturing”, ”VR application in intelligent manufacturing”, ”virtual engineering and smart manufacturing”, ”virtual design and smart manufacturing”, ”virtual reality and industry 4.0”, ”VR and smart manufacturing system”, and ”sustainable IoT-based manufacturing system and VR”. The search keywords were determined as the most frequently used words or phrases in the researched literature. Because the examined research was published between 2018 and 2022, only 359 publications met the qualifying requirements. We chose 227 primarily empirical sources by excluding ambiguous or controversial findings (insufficient/irrelevant data), outcomes unsubstantiated by replication, excessively broad material, or having nearly identical titles (Table 1 and Table 2).

Table 1. Topics and types of paper identified and selected.

Topic	Identified	Selected
Virtual training and education	18	9
Virtual engineering	31	23
Virtual 3D modeling	28	17
VR and smart manufacturing	127	104
Safety training through VR	58	17
Digital twin in intelligent manufacturing	46	33
Virtual design	51	24
Type of paper		
Original research	265	204
Review	55	23
Conference proceedings	14	0
Book	13	0
Editorial	12	0

[1] Source: Processed by the authors. Some topics are overlap.

3. Terminology for immersive virtual reality application in intelligent manufacturing

Human-machine interaction has lately been a prominent topic in smart manufacturing. The unique interactivity of VR innovation enables users to construct a virtual world and interact with it, allowing them to immerse in the digital world of the ifactory. Recently, many new VR innovations in intelligent manufacturing have sprung up, such as virtual engineering, virtual design, virtual 3 dimensional (3D) modeling, virtual maintenance, virtual inspection, safety training, operator 4.0, and ergonomic assessment, as shown in Figure 3, and the key technologies involved are shown in Figure 4 and Figure 5 respectively. To be specific, the VR technologies involved include 3 dimensional (3D) modeling, stereoscopic display, real-time rendering, human-computer interaction, as well as collision detection. Meanwhile, cloud computing, the Internet of Things (IoT), the real-time location system, and cyber security are the key technologies of smart manufacturing. All these concepts will be discussed in detail in this section.

Table 2. General summary of evidence concerning focus topics and descriptive results (research outcomes)

General summery	Examples
Intelligent manufacturing is a broad concept of manufacturing that has been under continuous development for decades, and some paradigms, such as smart manufacturing, are frequently used synonymously with intelligent manufacturing.	Kusiak, 1990; Rzevski, 1997; Oztemel, 2010; Hozdić, 2015; Burke et al., 2017; Zhong et al., 2017; Zhou et al., 2018; Zhong et al., 2017; Mittal et al., 2019.
Intelligent manufacturing has become a popular topic in recent years as a large number of papers generally review the literature on intelligent manufacturing in the context of Industry 4.0.	Kang et al., 2016; Jardim-Goncalves, Romero, and Grilo 2017; Zhong et al., 2017; Kusiak 2018; Zheng et al., 2018; Osterrieder, Budde, and Friedli 2020; Wang, Tao, et al., 2021.
With the rapid evolution of digital twin, the application of digital twin has found an increasingly wide utilization in smart manufacturing.	Son et al. 2022; Moiceanu et al., 2022; Keqiang Cheng et al., 2022; Arjun et al., 2022; Jinho Yang et al., 2022; Friederich et al., 2022; Lianhui Li et al., 2022.
VR and smart manufacturing are becoming increasingly important in manufacturing as technology advances, and virtual reality is playing an increasingly important role in the production and operations management.	Leonardo Frizziero et al., 2022; Tripathi et al., 2020; Ali Ahmad Malik et al., 2020; Corallo et al., 2022; Yuk-Ming Tang et al., 2022; Marko et al., 2022
The COVID-19 epidemic has caused more remote meetings and social estrangement in the year 2020. This will enhance the usage of VR in a variety of industries, including healthcare, tourism, and education; it may also hasten the pace of technological advancement in the industrial sector.	Singh et al., 2020; Kwok and Koh, 2021; Czifra et al. 2020; Silvia Fernandes, 2022; Thomay et al. 2022
Modern digital technology, which has significant commercial potential and significant technical drive, enables smart manufacturing.	Alessandro Umbrico et al., 2022; Joel Murithi Runji et al., 2022; David Wuttke et al., 2022; Mario Catalano et al., 2022; Devagiri et al., 2022; Phuong Thao Ho et al., 2022

[1] Source: Processed by the authors. Some topics are overlap.

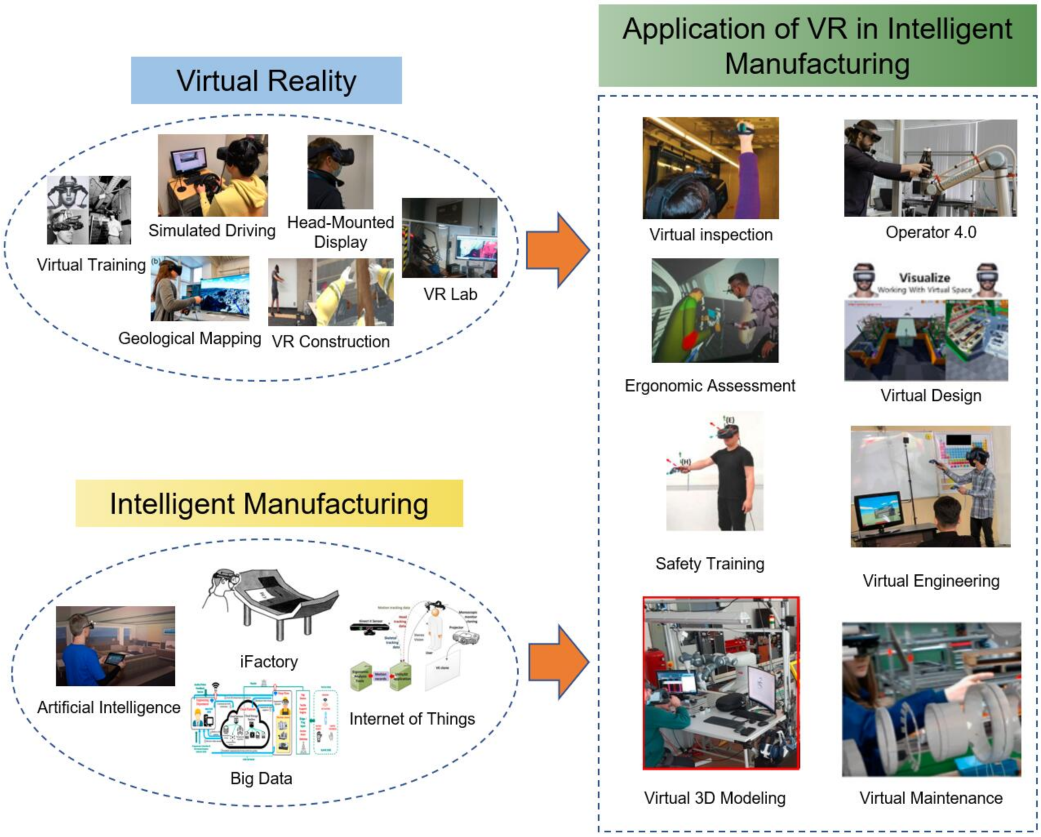

Figure 3. Applications for VR in intelligent manufacturing, including virtual engineering, virtual design, virtual 3D modeling, virtual maintenance, virtual inspection, safety training, operator 4.0, and ergonomic assessment [23–37].

3.1. Virtual reality

An enhanced human-machine interaction called virtual reality (VR) tries to recreate a realistic world. Additionally, players are allowed to roam around in this virtual reality setting [22], view it from various perspectives, grasp ahold of it, and modify it. The ideal virtual reality setting is frequently thought of as being in cyberspace [38]. It resembles a parallel universe of computers where data are cities of illumination. Information professionals use a specific VR innovation to access networks and navigate their information highways [39]. Additionally, the article covers the most recent advancements in VR.

Once the technologies underlying VR have made it feasible to create and implement useful and effective VR applications, it is vital to understand VR [40]. This in-depth and approachable investigation seeks to assist you in seizing this opportunity and provide you with the knowledge necessary to recognize and get ready for potential uses of VR in your industry, regardless of the subject [41].

Due to the wide range of disciplines, application areas, and system types that VR encompasses, as well as its specific research objectives and application needs, distinct categories of VR systems may be created from various angles [42]. The use of VR technology is widespread across a variety of industries, including the television and film business, education, design, healthcare, the aerospace sector, the military, and more [43]. Through computers, VR innovation creates a simulated environment that

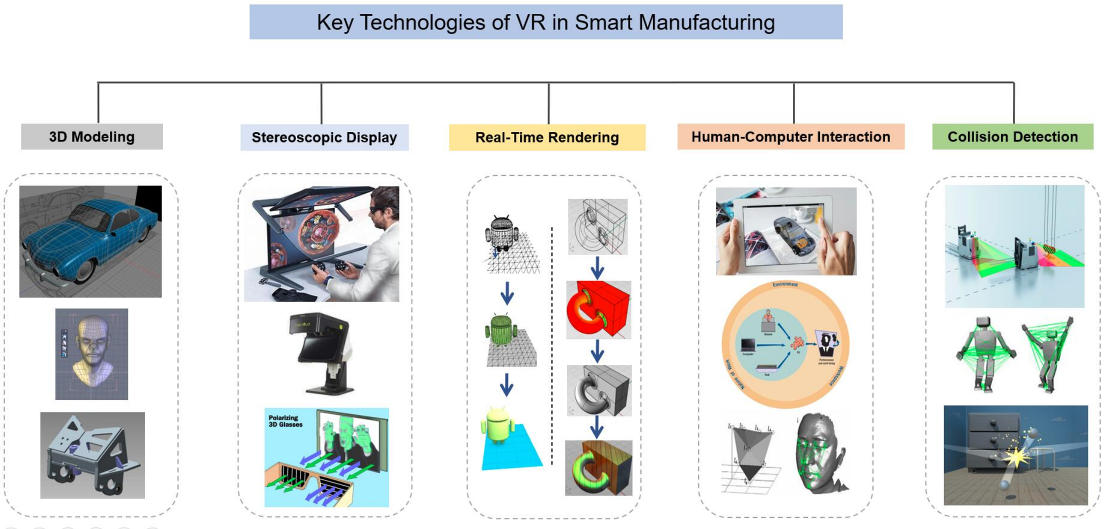

Figure 4. Key technologies of VR in smart manufacturing, including 3D modeling, stereoscopic display, real-time rendering, human-computer interaction, and collision detection (Source: Processed by the authors)

people may engage with directly through their senses of hearing, seeing, and touching. It also assists workers in many ways.

The term VR refers to an innovation that creates a simulated world via the use of computers, allowing users to have a firsthand sense of hearing, seeing, and touching. VR technology in the Chinese market has grown more developed and logical throughout the years. The integration and progress of VR are accelerating because of factors including the Internet of Things, cloud services, and 5G networks. It is important to note that recently discussed new technological ideas like the meta-universe as well as the digital twin (DT) have brought VR limitless creative potential and reignited interest in industrial growth. The key distinguishing characteristics of VR innovation are, generally speaking: immersion first. Users can get fully involved in a VE world thanks to its use. In this computer-created world, people may interact with their surroundings. The conception is the following. A virtual space for the user can be created via VR. By engaging extensively with their outer world, users can expand their views and grow to trust the VR setting.

3.2. *Intelligent manufacturing*

Modern monitoring, web, robotization, and AI are the foundations of intelligent manufacturing innovation [44,45], which achieves business operations, industrial design, as well as manufacturing processes, through awareness, human-machine interaction, decision-making, implementation, and feedback [46]. It may be said that it will enhance the fusion of data research and innovation [47].

Intelligent manufacturing has been developing steadily for many years as a comprehensive manufacturing idea [48–50], and [51–54] summarized and introduced the latest research advancements in intelligent manufacturing. In this area, certain paradigms, including smart manufacturing, are commonly used interchangeably with intelligent manufacturing [50,55]. The literature on intelligent manufacturing in the context of Industry 4.0 is typically reviewed in a significant number of articles from diverse aspects [56–59], especially the solutions to Industry 4.0. [60,61].

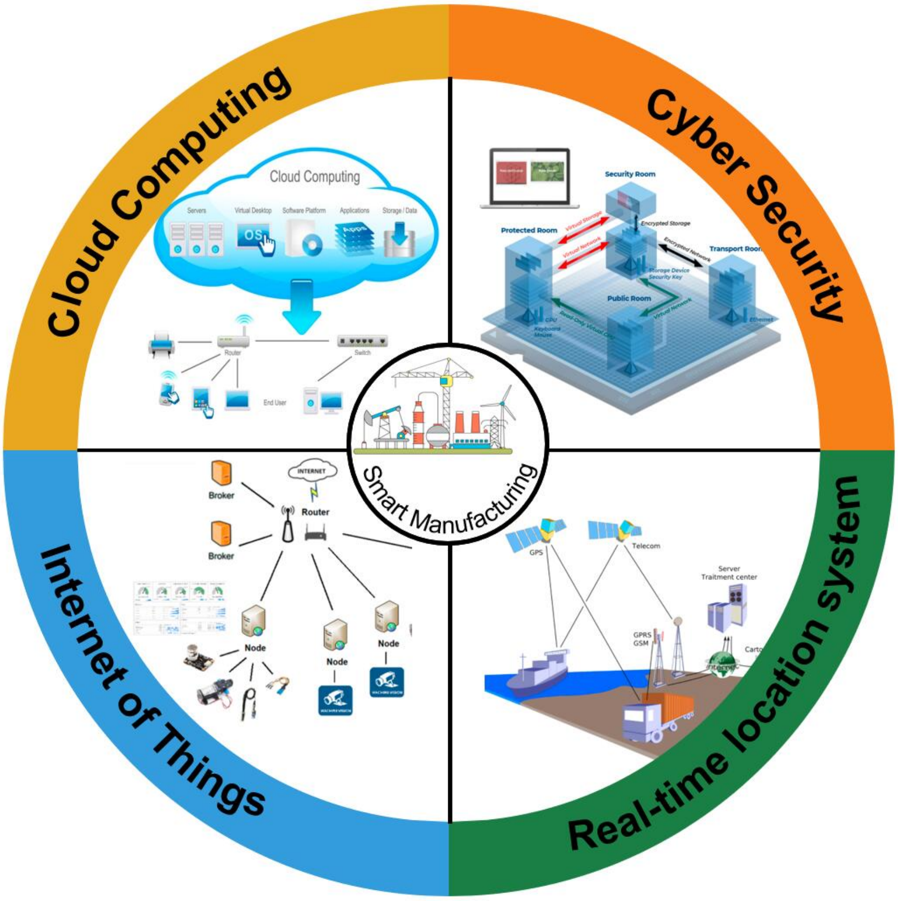

Figure 5. Key technologies of smart manufacturing, including cloud computing, the Internet of Things (IoT), the real-time location system, and cyber security (Source: Processed by the authors).

The fundamental difference between automation and intelligence is how knowledge is defined [62]. The basis of intelligence is an understanding of science, and smart production is based more on knowledge than practice [63]. Therefore, smart manufacturing encompasses both material and non-material processing procedures. In order to consistently produce high-quality skills and industries, it requires a reliable and stable knowledge production chain in addition to industry-university-research cooperation. Additionally, it features a complete and flexible resource supply chain [64]. New products with a high value are produced via innovation, and the industry must likewise develop and advance constantly [65].

Smart manufacturing, a sustainable manufacturing prototype [66], improves product design and manufacturing while reducing the consumption of materials, energy, and various wastes [67]. It does this with the help of digital modeling, data processing, interaction, and data systems. Recognize the significance of pollution prevention, emissions reduction, and recycling.

Smart manufacturing covers a large range of applications, such as Operator 4.0 and Industry 5.0. Operator 4.0 is a "clever and experienced operator who, if and when necessary, does 'work helped' by machines" [68]. The Operator 4.0 typology is important for better understanding the future roles of humans and robots in the Human Cyber-Physical System industries [69,70]. Traditional manufacturing organizations may readily incorporate the future contributions of humans in Industry 4.0 by building a typology and a transcript of available assets and talents. Those who collaborate with robots and intelligent machines are referred to as being in ”Industry 5.0” [71]. It is about using cutting-edge technologies like the Internet of Things (IoT) and big data to enable robots to assist humans in working more effectively and quickly. It gives the Industry 4.0 pillars of efficiency and automation a more human touch.

3.3. Art design

Applying the aesthetic sense to a style that is directly tied to daily life is what is meant by ”artistic design.” As a result, it serves both utilitarian and aesthetic purposes [72]. In other words, humans come first when creating art (from large to space environments, from minor to necessities of life). It is a full integration of material and spiritual activities in the growth of human society. To put it another way, it might be considered an unavoidable byproduct of the development of contemporary civilization [73].

Independence and comprehensiveness. In contrast to the conventional art categories, art design is always an autonomous art field with a wide range of study topics and service offerings [74]. Art design affects a wide range of aspects due to its extensive subject matter, including social, cultural, economic, commercial, technological, and others. And these things have an impact on its aesthetic standards. As a result, art is a product of life and influences it, both through behaviors and thoughts. The foundation of art design is creativity and practice, which reflect the holistic traits of the designer (such as the ability to express, perceive, and imagine). The criteria for aesthetics, rhythm, balance, and other elements of the notion of ”big design” are the same, despite the fact that various majors place varied emphasis on design expertise [75]. The architect must first develop a knowledge of the design item, whether it is a two-dimensional or three-dimensional design: a working grasp of the design object’s background culture, geology, history, and literature [76]. Because of the features of creative design, the artist is both a thinker and a performer.

Repairability. Creative alteration of a way of life to offer the potential of a new existence for humans is the major motive for artistic design rather than expression [77]. Artistic creations enable people to have more meaningful and quality lives, whether in daily life or in economic endeavors [78]. The ultimate purpose of aesthetic design is to make life easier, more pleasant, more natural, and more effective. A superb product is the pinnacle of artistic production; it is not the designer’s pure expression of self that makes a wonderful product [79]. For instance, the iPhone altered how people act today, but Jobs created Apple with the customer in mind [73].

With its form, performance, and worth, art design serves as a creative and inventive activity that satisfies the demands of both users and producers. In a broad sense, art design is the conceptual framework and development of a workable execution strategy aiming to accomplish a certain goal, as represented in a clear methodological approach. It describes a sequence of steps used to carry out a certain aim, conceive and construct an executable implementation plan, and clearly communicate it. of goods driven by the necessity to alter nature in the In a strict sense, it simply refers to the creation interplay between man and nature, encompassing all admirable ideas for the continuance and expansion of productive life. The fundamental goal of art design is to fulfill the user’s needs and increase the user’s affinity for the product. Additionally, the evolution of art design may provide insight into a society’s political, economic, cultural, and technical growth as well as the state of a certain social consciousness and ideology at a given moment. With the growth of the material economy and the raising of living standards, people’s interest in industrial product design has risen. Additionally, as their demands for industrialized product design increase, so does their quest for product quality and precision.

4. Immersive virtual reality application for intelligent manufacturing

Virtual reality (VR) is a word used to describe circumstances created by computers that may replicate physical presence in both reality and an imagined one [80]. In addition to the potential for smart manufacturing and VR, inevitable difficulties also resemble many useful innovations [81].

4.1. Recent advancements of virtual reality on intelligent manufacturing

VR, a fundamental technological advancement, makes it easier to integrate humans into such a system by giving them a way to engage with the digital environment of an intelligent manufacturing workplace.

4.1.1. Industry 4.0 and intelligent manufacturing

The term "industry 4.0" alludes to the fourth industrial revolution, even if it addresses topics like smart cities that aren't often categorized as industry applications in and of themselves. Recently, the relationship between industry 4.0 and virtual reality has become a popular research topic, and the latest research progress will be listed below.

As intelligent manufacturing spreads throughout a wide variety of industrial sectors, the manufacturing industry must take the lead in innovation to withstand the demands of global competition. The debate over augmented reality and virtual reality is merged with automated simulation in new system settings in Industry 4.0, according to R. Dhanalakshmi et al. [57]. The conclusion of the study elaborates on the problems and top advances in intelligent manufacturing for the research field of Factories of the Future (FoF).

In order to forecast production in real time and support it, industry 4.0 combines intelligent and networked production technologies, which results in sustainable organizational performance. In [82], Katarina Valaskova et al. offered a thorough examination of the numerous potentials for Slovakia's value-added automobile exports. Katarina Valaskova and colleagues also looked at the case study of PSA Group Slovakia, which emphasized the value of the Industry 4.0 idea in fostering the expansion of the nation's exports. However, as the study was only done in one nation and the data are not yet public, it has certain limitations.

Studies from the past have looked into the connection between work and Industry 4.0 technology. For the purpose of systematizing this information into a unified and comprehensive viewpoint on Industry 4.0 methods and work, Dornelles et al. in [83] chose a thorough literature review technique. The study provides information that will be helpful for future research and the development of operational procedures in the context of Industry 4.0 by demonstrating how various production operations and worker skills may be supported by Industry 4.0 technology.

Industry professionals use smart and lean manufacturing to enhance shop floor management systems in industry 4.0. Shop floor management is used to improve output while limiting operational performance. In [84], Varun Tripathi et al. exploited smart manufacturing ideas to establish an open invention technique for improving sustainability in factory floor frameworks in industry 4.0. Within the confines of Industry 4.0, the suggested technique would offer sustainability in the shop floor management system.

Nearly every element of people's life is now impacted by megatrends, including individualization, climate change, emissions, energy and resource shortages, urbanization, and human well-being. Numerous studies have looked into various approaches, with newer studies focusing on Industry 4.0 and smart manufacturing technologies and numerous research efforts focusing on urban production. As a response to the current megatrends, Seyed et al. in [85] looked at integrating smart factory technology with urban production. In order to examine the advantages, difficulties, and connections, a literature analysis on relevant disciplines, including mass personalization, sustainable products, urban factories, and smart factories, was also carried out. Urban smart factories are offered as a combination of smart factory technology with urban manufacturing, and they have three key features: they are resilient, sustainable, and human-centric. To the author's knowledge, no definition of this kind has ever been put out.

4.1.2. Digital twin in intelligent manufacturing

As we go toward intelligent manufacturing in the Fourth Industrial Revolution era, the digital twin (DT) is becoming increasingly important. This section will review the current papers on the issue of the digital twin and virtual reality.

There are various studies that adapt and examine DT at real manufacturing sites in order to realize a smart factory, yet it is important to carefully assess which aspect of DT is used and what purpose it serves in production. In [86], Son et al. analyzed and categorized earlier publications using the hierarchical level axis of the Reference Architecture Model Industry 4.0, the intended function of DT, as well as other product life cycle management stages. This paper suggests options for future research on DT and a system architecture that can carry out all of DT's duties via a thorough examination of the shortcomings of previous and current research.

Future technological advancements that will affect the world's industries as we now know them include the creation of the digital twin. Therefore, in order to further innovate and enhance the working process across all industries, it is essential to grasp the relationship between the digital twin, smart manufacturing, and Industry 4.0. Utilizing data from the Web of Science, Moiceanu and Paraschiv in [87] conducted a bibliometric analysis of the output of scientific papers on advanced automation and intelligent manufacturing with an emphasis on Industry 4.0.

The smart manufacturing system (SMS) is regularly changed to meet the demands of product customization. A semi-physical simulation approach for testing and evaluating industrial software is provided based on digital-twins-driven technology to swiftly assess the dependability and flexibility of the program while changing the SMS for new or improved product orders. In [88], Keqiang Cheng et al. discussed the use of digital twins in compressive strength testing of the industrialized software application of smart manufacturing and offered a digital-twins-based semi-physical simulating test and assessment technique for the SMS operating system. The efficacy and viability of the suggested technique are confirmed, and the testing and verification time of industrial software is greatly decreased, by creating a semi-physical simulation manufacturing line model for stepper motors.

A challenge in information visualization is interacting with and visualizing massive amounts of data. In [89], a digital twin of an intelligent manufacturing workplace with a remote monitoring dashboard is shown by Somnath et al. The construction of the digital twin was discussed, and then three user tests on the sensor dashboard's interface and visualization features were shown.

Reconfigurable manufacturing lines necessitate the human creation of production line models for every reconfiguration since conventional simulation technologies do not converge with actual manufacturing systems. In [90], Jinho Yang et al. present a digital twin-based integrated reconfiguration assessment application that synchronizes with real-time manufacturing data and provides accurate, automated simulation functionality to build and analyze a manufacturing system. The findings show that, compared to current methodologies, the suggested application offers faster and more precise reconfiguration evaluations. The results of this study should make it easier to make accurate and consistent decisions when assessing the various production line performance indicators.

Adoption of digital twins in smart factories, which simulate current production system conditions and update them in real time, results in higher productivity as well as lower costs and energy use. A general data-driven architecture for the automatic development of systems as the foundation for digital twins for Industry 4.0 was presented by Friederich et al. in [91]. The uniqueness of their suggested framework lies in its data-driven methodology, which takes advantage of recent developments in machine learning and process mining approaches as well as ongoing model validation. The study has reduced and completely defined—if not entirely eliminated—the requirement for specialized expertise in order to extract the appropriate simulation models.

A digital twin creates the virtual model of a physical entity in a digital way, promotes the interaction and integration of the physical world and the information world, and builds a reliable bridge for industrial information integration. With the rapid evolution of the digital twin, its application has found an increasingly wide range of utilization in smart manufacturing. It was demonstrated in [92] by Lianhui Li et al. that the quantitative green performance evaluation of smart manufacturing (GPEoSM) system, which is driven by digital twins, is efficient and improves the green assessment of smart manufacturing. The outcome demonstrates the efficiency of the digital twin-driven GPEoSM framework and how it improves the green performance assessment of smart manufacturing.

4.1.3. Virtual engineering, designing, and training

The amount of automation, product and process flow, production scheduling, supplier agreements, and facility layout are just a few of the numerous variables that affect how productive a manufacturing company's production system is. In [93], eight years of innovation activities were continued by Daniel Nfors and Björn Johansson in order to comprehend the difficulties in brownfield plant layout design and whether or not virtual engineering utilizing accurate models may reduce or remove those difficulties. The paper shows that, through the use of virtual engineering, businesses can streamline the process of planning the layout of brownfield factories and make informed choices that will improve sustainability by reducing the likelihood of costly errors, boosting employee engagement, and necessitating less travel.

Digital human models (DHMs) are fictitious depictions of people. They are employed, among other things, in the development of ergonomic plant layout evaluations. DHM software tools are difficult to operate, so engineers must undergo extensive training before using them. In [94], engineers can readily work with DHMs thanks to the VR application that Geiger et al. described. The VATS layout was contrasted to the current WIMP interface in the user research that they also show. Their software offers a reality-based user interface that enables users to assemble objects in virtual reality while manipulating the environment with their own hands.

The utilization of contemporary information and communication technology is essential for long-term manufacturing firm sustainability in the present global competitive climate. The Digital Factory subsystem at the University of Zilina's Industrial Engineering Department features applications of virtual and augmented reality, according to Gabajová et al. in [95]. The user must wear special glasses in the so-called cave chamber, and his mobility is restricted to a certain area constructed of walls, as can be seen in Figure 6. This study's primary objective was to investigate and describe the potential benefits of immersive technology for classroom instruction.

Figure 6. CAVE (Computer Assisted Virtual Environment) [95].

It may be necessary to use robots from various manufacturers in some processes, so the design of these multi-robot systems is essential to ensuring the highest level of quality and efficiency [96]. A novel scientific method for smart manufacturing design, improved implementation, and real-time tracking in operation was presented by Pérez et al. in [97]. It is based on the creation of a digital twin of the manufacturing process with an immersive virtual reality interface to be used as a virtual testbed prior to the physical implementation.

The construction industry (AECO—architecture, engineering, construction, and operation) has several challenges and barriers in an effort to reduce its accident rate, which is one of the highest among all industries and is presently increasing again after a period of relative stability. In [98], Mora-Serrano et al. examined the intersection of existing OHS training methods and VR possibilities, using a series of items identified as critical to progress toward a personalized remedy that actively engages workers in their education, promoting mechanization in the formation of these VR experiences. According to the research, technological advances have made it possible for virtual reality technology to produce training scenarios for industry experts with ever-shorter production durations.

In [99], Chad McDonald et al. outlined two initiatives aimed at making child welfare systems increasingly capable and efficient by utilizing improved learning methods such as VR for training and enhancing collaboration among child welfare and healthcare experts. Insights from these two case studies' findings can be used to plan and execute long-lasting changes in child welfare strategies for families and kids who have been reported for suspected abuse.

The adoption of experimental training is essential in reducing occurrences at construction sites since the absence of experience-based training has become the main contributor to accidents that might have been easily prevented in construction regions. Building an actual test site and replicating the construction scenarios are not achievable due to a lack of training resources. According to Zheng Xu and Nan Zheng in [100], the adoption of the suggested VR platform might yield several benefits, including becoming an ideal tool for construction instruction and stimulating human-machine interaction research. This study shows that the nomination of the suggested VR platform might have several advantages, serve as a useful tool for educating construction workers, and encourage research into human-machine interaction.

4.1.4. Virtual reality in the production and operations management

VR and smart manufacturing are becoming increasingly important in manufacturing as technology advances. Leonardo Frizziero et al. in [101] propose a case study of IDeS applied to the creation of a new sporting sedan. The project is disassembled into a succession of phases, each with a distinct aim, culminating in the production phase. The major functions of the factory production line are virtual-real data synchronized telecommunication and VR mapping technology, which enable the hyper-real, digitalized simulation of objects using virtual reality technology [102]. According to Tripathi et al. in [84], the technique might offer a sustainable production system and problem-solving skills that are essential for managing production on this factory floor in the setting of Industry 4.0. These articles demonstrate that virtual reality and smart manufacturing can be beneficial in the production process, and they not only reduce the cost spent on the assembly line, but also make it easier for production management.

In order to accomplish hybrid automation in manufacturing, the idea of human-machine interaction has gained a lot of attention in recent years. The beneficial interaction between humans and robots is being benefited by a type of hybrid automation [103–105]. A unified framework is created by Ali Ahmad Malik et al. in [106] to merge VR with human-robot simulation. They study the technical advancements in virtual reality for the creation of human-centered production systems. In order to design a process plan, optimize the layout, and develop a robot control program, the event-driven simulation helped estimate the cycle durations between humans and robots.

Model-based frameworks can better meet user configuration needs while also providing greater clarity and transparency into how processes and data processing are carried out in the Big Data Analytics pipeline.In a complicated industrial environment, Corallo et al. in [107] offered theoreticians and management specialists helpful evidence for administering actual data analytics and implementing a workflow that solves particular analytical aims, driven by user needs and developer models.

Demand forecasting, inventory management, and production management have long been crucial concerns for the sectors, particularly in light of the global economic recession. The survey used in [108] by Yuk-Ming Tang et al. is for a tiny textile firm, and it serves as a means of illustrating the suggested digital framework in the store as well as the outcomes of sales forecasts and stock management.

One of Industry 4.0's four smart dimensions, Smart Working (SW), has had a substantial influence on businesses' operational activities by integrating cutting-edge technology into employees' daily tasks. In [109], Marko et al. offered a complete review of SW solutions, the characteristics that distinguish them, the aims of their application, and the motivation for the suggestion to apply a proven, comprehensive model for measuring the performance of SW systems and technologies.

In order to evaluate and validate cooperative workplaces from an ergonomic standpoint, Teodorico Caporaso et al. in [110] offer a revolutionary virtual reality system that uses wearable sensors (Figure 7). The major goal is to demonstrate in real time, within the immersive virtual world, the ergonomic evaluation based on a muscle activity analysis [111]. The findings demonstrated that the approach may be successfully used in the study of human-robot interaction to provide workers with a sense of self-awareness regarding their physical circumstances.

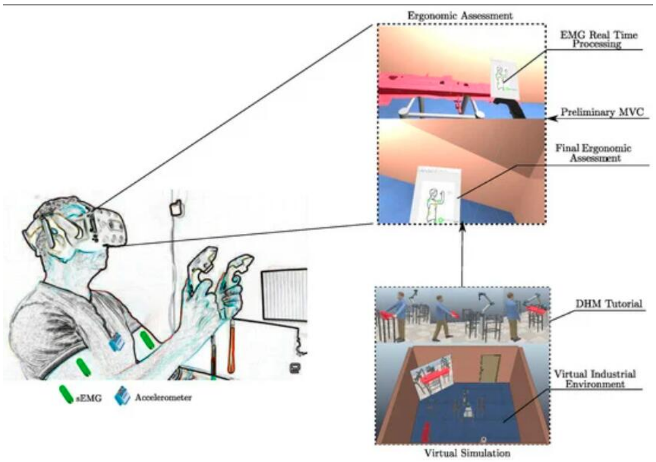

Figure 7. A schematic representation of the system architecture. An illustration of an actual situation is shown on the left: the user is wearing wearable sensors (such as an accelerometer and sEMG) and VR equipment (i.e., a headset and controllers). A photosequence of the DHM instructional (top) and a picture of the virtual world make up the ”Virtual Simulation” block, which is located in the bottom-right corner (bottom). The ”Ergonomic Assessment” block with the input data, including the virtual simulation and the ”Preliminary MVC,” is located in the upper right corner. An image of the ”EMG Real Time Processing” is shown in the block at the top, and an image of the ”Final Ergonomic Assessment” is shown at the bottom [110].

DHMs, or digital human models, are necessary for applications involving virtual manufacturing. Furthermore, studying novel DHM applications has grown to be a significant academic research area. The theoretical and analytical foundation for using virtual reality to inform decision-making for intelligent manufacturing is provided in [112] by Wenmin Zhu et al. The research demonstrates that the use of DHMs can increase the effectiveness and realism of virtual manufacturing, and in the near future, DHMs will be more thoroughly researched and used in a variety of manufacturing industries.

The application of digital technology to intelligent transportation is covered in [113]. The essential stages toward real-time (RT) manufacturing optimization utilizing a simulation model, VR techniques, and tools are presented in this study. The article's main contribution is the use of VR methodologies and discrete system simulations for real-time decision-making.

One of the most common ailments associated with manual employment is musculoskeletal. Employers all across the globe incur significant expenditures for both prevention and treatment. Ilona Kačerová et al. [114] propose a novel approach for designing an ergonomic workplace. Figure 8 shows the setup before ergonomic testing with the MoCap system. This approach takes advantage of modern technology and promotes not only an overall improved manufacturing process design but also improved ergonomics. The results of the study show that an assembly workstation may be evaluated for ergonomics using VR technology and MoCap suits. With precise evaluation capabilities, all of the working positions that a person assumes throughout an activity may be examined, not only the upper

Figure 8. There are phases of the study: VRb, VRa, NonVR, and Classic. This figure shows sample VRb directions [114].

limbs.

A significant possibility to boost the productivity and international competitiveness of macro- and microeconomic entities inside the European Union as well as globally may be observed in the integration of smart systems in industrial logistics. Woschank et al. in [115] focused on the study topic of industrial transportation in manufacturing businesses in order to examine the possibilities of intelligent integration. The authors also provide a framework for the application of smart transportation to industrial businesses.

4.1.5. Innovations related to virtual reality in intelligent manufacturing

The development of efficient, secure, and dependable control paradigms is complicated by the cohabitation of autonomous robotic entities and people. In [116], Alessandro Umbrico et al. advocated integrating modern artificial intelligence, control, and AR technologies to improve the adaptability and flexibility of collaborative systems. In Figure 9, two applications running on the Android tablet Samsung Galaxy S4 and the augmented reality headset Microsoft HoloLens 2 were used to launch the HS-SH interaction module. The successfully implemented technology modules in a real-world production scenario demonstrate the technical viability of the strategy. Future research will examine the applicability of the suggested strategy with users having various talents and attributes, as well as on the shop floor.

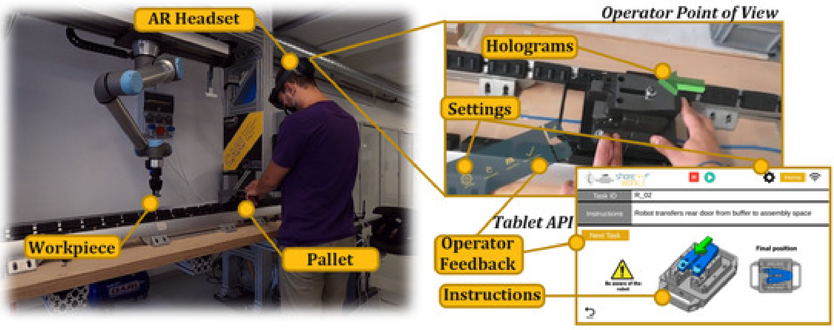

Figure 9. Demonstrator setup and HS-SH interaction module [116].

Technical equipment maintenance is essential for production to maintain productivity with the fewest possible downtimes. Adopting AR technology may help with the elimination of unexpected disruptions and real-time monitoring of equipment health [117]. The existing research on AR technology in the upkeep of industrial organizations from 2017 to 2021 was thoroughly reviewed in [118] by Joel Murithi Runji et al. The evaluation specifically looks at how these studies met users' requirements and pinpoints areas that need more investigation.

The usage of AR devices by businesses to enhance production ramp-up procedures is on the rise. Although these gadgets seem useful, little is known about how they might affect behavior and productivity in the workplace more generally. In [119], David Wuttke et al. presented empirical facts connected to AR in the setting of production ramp-up, examined the benefits and drawbacks of AR, and tested four hypotheses, resulting in a more comprehensive understanding of AR use in production process ramp-up.

Although the Digital Twin in manufacturing offers a variety of advantages, more work is still needed to fully implement this idea, especially in terms of real-world applications. Mario Catalano et al. in [120] proposed and discussed a theoretical foundation for XR applications that is based on digital twins. The most practical number of operators and Automated Guided Vehicles to utilize in the production area may be determined using the suggested framework. The majority of future work will center on trials using the 5G network, which can provide an accurate and timely real-time alignment between the physical world and the digital twin.

With many sectors and academia realizing the value of their adoption, the combination of AR and AI is expected to become the next significant path in the coming years. In [121], a thorough analysis of current developments in AI-enabled AR platforms, techniques, methodologies, and applications, as well as the difficulties associated with applying AI to AR, was offered by Jeevan S. Devagiri et al.

AR may also provide operators with immersive interfaces to boost productivity, accuracy, and autonomy in the quality sector, where numerous production processes necessitate high quality and close to zero mistake rates to satisfy the demands and safety of end-users. In [122], Phuong Thao Ho et al. conducted a systematic literature review (SLR) to conclude about the emerging interest in using AR as an assisting technology for the quality sector in an industry 4.0 context. In order to categorize articles into different layers and eventually integrate them into a systematic design and development approach, an AR architecture layer framework has been improved. This will enable the creation of long-term AR-based solutions for the quality sector in the future.

Efficiency and quality are essential metrics for any manufacturing business. There is a severe lack of skilled people across the manufacturing line for sophisticated assembly activities in many businesses. Ze-Hao Lai et al. in [123] offer a worker-centered system consisting of multi-modal AR instructions with the assistance of a deep learning network for tool recognition to decrease the amount of time and error in an assembly operation. A more varied simulation environment is offered by VR technology for the development of simulation technologies. With the help of the integrated system, a productive, adaptable smart AR training system that can sense needs, characterize them, and improve worker performance has been developed and put to the test.

AR and VR are developing as next-generation display platforms for deeper human-digital interactions as a result of the quick advancements in high-speed transmission and processing. In order to construct human-centered production systems, VR technology is being explored in [124]. It also seeks to establish a unified framework to combine human-robot simulators with VR. The research shows that compact microdisplays with high peak brightness and good stability are now possible thanks to recently developed micro-LEDs. Metasurfaces/SRGs, and micro-LEDs are projected to perform better in AR and VR applications as a result of future improvements in device engineering and manufacturing techniques.

Most workers shun traditional shoe manufacturing's several procedures because of the loud noises and unsafe working conditions. To create an automated process, a robot-based shoe production system is required. In [125], this paper proposed a new robot-based shoe manufacturing automation system that includes an automatic robotic solution for replacing the manual manufacturing processes of the upper and sole. The suggested systems and procedures may be used for upper and sole manufacturing processes, according to evaluation trials in a model production line.

The adoption of smart manufacturing concepts and technology into industrial practice has received a lot of attention over the last two decades. These initiatives have received financing from European research and innovation programs, which have brought together research and application parties. Grefen et al. in [126] gave an overview of a group of four interconnected projects upon this European level that are intended to advance smart manufacturing. The projects are focused on linking enterprise-level business activities and industrial machinery, and processes on smart manufacturing shop floors. Both future academic initiatives and commercial advancements into digital assistance for smart industries can benefit from the findings of the paper.

The upcoming phase of the manufacturing industrial revolution is being driven by intelligent technology. The implementation of a customized virtual reality application in a simulated environment and human-machine interaction are introduced by Yuan Zhou et al. in [127]. According to this study, Chinese manufacturing companies can switch between the three technical paradigms of intelligent manufacturing through a number of non-linear paths. According to their skills and industry-specific characteristics, Chinese companies may plan their own upgrading paths toward intelligent manufacturing, according to this conclusion, which can also be applied to other catching-up economies. This essay offers manufacturing companies, decision-makers, and investors a strategic roadmap that serves as an explanation.

Under this transformation, known as "Industry 4.0," a robot now works alongside human operators in factory production.In such settings, safety for both people and robots becomes essential to a successful production cycle. In [128], an innovative safety response system was presented by Kiangala et al. for a small manufacturing facility, through which a robot might learn the path that would be free of obstacles and lead to the nearest safety escape in the event of an emergency.

The COVID-19 issue has caused many activities and sectors to cease, but because of digital technology, individuals now have greater access to public services since resources are being used more efficiently. In [129], Silvia Fernandes initiated a conversation about the key requirements and developments of IoT in the aftermath of the epidemic. The link between creation and city intellect is investigated in order to identify the key contributing and restricting aspects, as well as to define future approaches toward better services.

In order to assist the entire advanced manufacturing chain through digitalization, Christian Thomay et al. posited the AQUILA system in [130], laying the foundation for quality assurance in situations where supply chains are interrupted and travel options are limited as a result of the COVID-19 pandemic. The framework will use wearable eye tracking in conjunction with an augmented reality display and smart glasses to provide hands-free display of process-relevant interaction, mental load monitoring, and gaze-based interaction methods. These technologies will work together to enable the implementation of quality assurance and testing methods as well as the realization of evidence-based training scenarios.

Since the introduction of augmented reality and virtual reality, Industry 4.0 has been transforming the entire industrial experience in intelligent manufacturing: profit-economic growth has increased dramatically, laying a solid foundation and allowing customers to benefit from purely automated and artificially intelligent processes.

4.2. Challenges and benefits of VR and intelligent manufacturing

The industrial sector contributes to innovation leadership throughout the vast range of manufacturing industries in order to meet demands from the global competitive environment. The whole supply chain, from clients to manufacturing, must be entirely automated. All types of manufacturing systems, including intelligent manufacturing, will face difficulties [131–133]. The application of VR in intelligent manufacturing will present obstacles since sensors and fundamental intelligence skills will be crucial in the development of manufacturing [134]. The wearer's comfort is one of the major issues with VR. According to research, having a VR equipment for an extended period of time might make the user feel uncomfortable, feeling weak and disoriented while reentering the equipment [135].

VR and other technologies have transformed the entire industry. The transformations of education and entertainment are among the ones that most directly affect the general population [135]. VR is altering how we now educate, increasing the variety and allure of online and remote learning [136]. The use of VR in healthcare is also impressive. For example, VR aids in the development of telemedicine diagnosis technology and makes it easier to stop the propagation of viruses. It also offers a reliable, effective, and cost-effective simulation for medical training environments. The use of VR in intelligent manufacturing would be the major topic of this article. And the growth of the smart manufacturing sector has been somewhat accelerated by the advent of VR [56]. It is important for powering the intelligence of industry equipment.

5. Related work

Recent years have seen rapid development of virtual reality and intelligent manufacturing, and the combination of the two areas is becoming closer. Meanwhile, many concepts related to this area, such as extended reality (XR), augmented reality, and the digital twin, have been explored and reviewed by many scholars. This section will go over the recently published reviews on the topic of virtual reality application in intelligent manufacturing as well as its related concepts.

The literature's consistency in defining, thinking through, denoting, and developing technically the ideas of smart manufacturing (SM) or intelligent manufacturing (IM) has not received much attention from an evolutionary standpoint. To fill this gap, Baicun Wang et al. [59] perform a qualitative and quantitative investigation of research literature to systematically compare inherent differences of SM and IM and clarify the relationship between SM and IM. The research of the growth of SM and IM gives practical recommendations for understanding and implementing SM and IM in organizations or areas with a low degree of SM and IM development. Because manufacturers are the primary implementers of SM and IM, it is recommended that more attention be paid to key technologies such as CPS, big data, cloud computing, IoT, and AI, as well as human/staff training tailored to their specific situation, regardless of which SM/IM paradigm is used.

Big data motivated analysis, one of the key AI technologies, enhances competitiveness in the manufacturing market by utilizing the potential and concealed knowledge value of industrial big data. It also assists enterprise leaders in making informed decisions in a variety of complex manufacturing settings. Chunquan Li et al. [137] present a theoretical analysis foundation for big data-driven innovation to direct decision-making in intelligent manufacturing, demonstrating fully the applicability of big data-driven technology in the intelligent manufacturing sector, including key benefits and internal motivation. Specifically, this paper proposes a conceptual paradigm of intelligent decision-making using industrial big data-driven techniques, which offers insightful ideas for the difficult problems and potential future research paths in this area. The distance between the two research disciplines concerned is this study's principal shortcoming. The framework is expanded upon and thoroughly investigated in this study, along with the creation of software systems and their application to industrial manufacturing.

The industrial sector is transitioning from automation to intelligence in the framework of Industry 4.0. Through a methodical literature survey, Liping Zhou et al. [138] discuss the state of the art, current issues, and potential future directions of IM-related production and operations management (POM) research. Five research themes—value generation mechanisms, production planning, resource configuration and capacity planning, scheduling, and logistics—are the main topics of the study and debate. Regarding the practical applications, the conclusions and revelations from this study may offer broad support for enhancing the use of POM-related techniques in real-world manufacturing administration.

Virtual reality, augmented reality, and mixed reality are examples of extended reality technologies that improve and assist Industry 4.0 in a variety of contexts. For the purpose of disseminating such a revolutionary environment, Leonor Adriana Cárdenas-Robledo et al. [139] concentrated on analyzing the essence and application of extended reality and reporting the evaluation of 287 approaches gathered from 2011 to 2022, categorized in the proposed taxonomy. The findings suggest that industry 4.0 has accepted the application of these technologies based on the sample of studied works. This study demonstrates the tools and primary tools used in XR applications, lists the key application areas, and focuses on different tasks. Additionally, it provides hints regarding the possible growth of future applications, which will have a significant influence on a variety of human activities at home and at work in addition to industry 4.0.

The applications of AR/MR that span several dimensions, facets, and levels have captured the interest of academics in the area of smart manufacturing in the past few years. In [140], Wang et al. reviewed the most current works and investigated the technical elements of manual operation instructions that have emerged in the past 30 years in existing research, programs, and practices. It is important to note that this work offers in-depth academic knowledge for the creation of AR-based assembly instructions, giving researchers in related domains uncommon insights. It will, in essence, aid researchers in creating AR instructions.

In the age of Industry 4.0, a production process that has included new integrated manufacturing technology is known as a smart factory. The complexity of the present production environment has increased the significance of human-machine interfaces (HMIs). In [141], to identify intelligent factory operations, tasks, information kinds, contact modalities, and their influence on human workers from the viewpoints of human factors and HRI, Naveen Kumar and Seul ChanLee performed a systematic literature review of HMIs. In addition, this paper analyzes the background of HMIs' practical application in smart factories and provides HMI advice for designers, users, and researchers. These discoveries shed light on how HMIs are created in modern smart factories.

The concept of "Industry 4.0" is increasingly recognized as distinctive. It assumes that communication and information technologies will be widely used, which will boost organizational flexibility and performance. Industry 4.0 and its flexible manufacturing system (FMS) potential were explored by Mohd Javaid et al. in [142]. Different flexible Industry 4.0 technology-based approaches are described in this study after several Industry 4.0 practices for improving FMS efficiency have been examined. Increased flexibility is among the most important advantages of using virtual infrastructure that is supported by a service provider. The underlying computer resources can be adjusted to fluctuating rates of utilization by using auto-scaling, which is a feature of cloud services.By increasing production flexibility, Industry 4.0 enables a facility to react swiftly to market developments.

Researchers and practitioners are exploring methods to connect the two in order to enhance people's lives across a variety of disciplines as the line between actual and virtual life becomes increasingly blurred. Designing Digital Twins (DT) is a cutting-edge idea with a wide range of implications and applications, including education, training, worker protection, and production. Künz et al. conducted a PRISMA-based research review of academic publications and journal articles exploring the use of MR and AR for DT in [143]. The main conclusion of this study is that the evaluated articles place a lot of emphasis on the technology itself while ignoring user-related variables. Therefore, researchers in this field should consider the value of usability and incorporate consumers at all phases of their work.

The sudden development and unrestrained worldwide spread of COVID-19 illustrate the incapacity of the present healthcare system to quickly respond to public health catastrophes. Ishwa Shah et al. in [144] provided a current assessment of the utilization of blockchain, AI, AR/VR, and IoT for battling the COVID-19, taking into account diverse applications. These innovations provide brand-new, cutting-edge efforts and COVID-19 use cases. This paper provides an examination of the applications of blockchain technology, AR/VR, AI, and IoT for battling the COVID-19 epidemic. These innovations provide brand-new, cutting-edge efforts and COVID-19 pandemic use cases.

Users of VR may develop motion sickness symptoms, often known as VR sickness or cybersickness. Eye fatigue, confusion, and nausea are just a few of the symptoms that can make consumers' VR experiences less enjoyable. The issues of using VR technology for near-eye display devices are discussed in this article as possible solutions [145]. The findings showed that the number of modalities in a virtual world can influence how high-fidelity effects on VR sickness are affected. This discovery raises the possibility that in order to lessen pain, multi-sensory information may be needed.

6. Discussion

To sum up, virtual reality is an advanced technology that can generate virtual environments to simulate the real world or to visualize phenomena invisible to the human eye. By reviewing over one hundred papers on virtual reality applications in intelligent manufacturing, we have summarized the state-of-the-art, current problems, as well as future trends in this field, which will be listed as follows.

State-of-the-art:

As summarized above, virtual reality is playing an increasingly important role in intelligent manufacturing, and the advantages of virtual reality technologies have grasped the attention of the academic field. The COVID-19 epidemic has caused more remote meetings and social estrangement in the year 2020. This will enhance the usage of VR in a variety of industries, including healthcare [145], tourism [146], and education; it may also hasten the pace of technological advancement in the industrial sector [147]. By reviewing the latest papers, the major advantages are listed below.

1. Virtual reality can shorten the cycle time. Sometimes the business models of enterprises make it difficult to keep up with market trends. Through the use of virtual reality, the supply line and prototype product design can be modified promptly so as to shorten the time needed to design, test, and control quality before the product is launched.

2. Virtual reality can significantly reduce accidents in production. Through the virtual simulation of the working environment, workers can learn how to operate the facilities properly in the factory in advance, thus lowering the risk of accidents caused by improper operation or neglect.

3. Virtual reality helps improve product quality. Specifically, virtual reality makes it possible for remote teamwork and can also boast efficiency for employees by offering a virtual and immersive working environment, as is indicated in [106, 148, 149]. Also, through virtual reality, design errors can be found promptly, thus reducing quality issues on the assembly line. Meanwhile, customer loyalty will also improve thanks to quality assurance and quality control in virtual reality.

Current problems:

1. Price: Most virtual reality devices are expensive, and the high price tag has hampered the wide adoption of virtual reality devices in intelligent manufacturing.

2. Technical bottleneck: Due to the low refresh rate and insufficient resolution, some users may suffer from dizziness as soon as they put on a VR device. Some head-mounted displays have a large size, which causes pressure on the user's head and will also bring about fatigue [145, 150].

3. Application area: Though virtual reality has been a promising technology applicable in various application domains such as training simulators, medical and health care, education, scientific visualization, and the entertainment industry, the application area in intelligent manufacturing is relatively narrow. For example, in [81, 106, 123], virtual reality is mainly used to provide data for guiding users to complete their work. However, it cannot fully replace human labor.

4. Depth of application: Most virtual reality innovations stay in the conceptual phase. Specifically, there is no way for users to actually enter the virtual world. For instance, in [113], the authors present VR methods for real-time (RT) manufacturing optimization. However, the users are not so much entering the simulated environment of manufacturing as experiencing it. Furthermore, the general public's perception of virtual reality and intelligent manufacturing is still based on audio-visual

entertainment.The manufacturing industry needs to provide more innovation to meet the competitive pressure brought about by the wide-ranging globalization of smart manufacturing. According to the European Commission's (EC) vision for the way forward, a new production system model should address the problem of transformable, networked, and learning factories, depending on several drivers such as high performance, extreme customization, environmental protection, excellent production efficiency, resources, outstanding human potential, and significant knowledge creation [151].

Future trends:

In the future, the combination of various technologies will go deep [152], and it is likely that intelligent manufacturing will combine big data processing, artificial intelligence, advanced robotics technology, and virtual reality innovations. The interconnection between these technologies will optimize manufacturing operations and reduce energy and labor requirements [153].

In addition to introducing the use of VR in manufacturing, this essay elaborates on the notions of intelligent person factors and VR that are connected to one another. The primary development path for the worldwide manufacturing sector is intelligent manufacturing. Countries are encouraging the quick development of smart manufacturing in an effort to gain an advantage in the highly competitive market. A novel method of human-machine interaction and special chances for the advancement of intelligent manufacturing are provided by virtual reality technology. The use of smart technology has been crucial to the improvement and modernization of the manufacturing sector, even if the present commodity of the smart manufacturing area is not yet mature enough. In the future, more efforts will be put into this area, and it can be expected to see a huge step forward in the next few years as immersive virtual reality will empower intelligent manufacturing in many ways. At the same time, a commercial virtual reality device will be developed and made available in different areas. Above all, the difficult techniques could be natural human-machine interaction techniques to make virtual reality much more accessible for manufacturing applications.

SWOT analysis of the work:

1. Strengths: The strength of the work lies in the careful selection of papers. In this process, we have paid close attention to the data of publication, sources of information, as well as the impact factor to make sure all the articles cited are related to the title and can reflect the latest trend of virtual reality application in manufacturing.

2. Weaknesses: Despite the previous efforts, this work still has many weaknesses. In terms of the methodology, we have limited choices in literature selection since there hasn't been much progress on the combination of virtual reality and smart manufacturing. Moreover, this work is specified in the context of virtual reality in an intelligent manufacturing scenario, and the related concepts such as extended reality, augmented reality, and mixed reality are not discussed in detail.

3. Opportunities: Through a systematic literature review, this work will likely provide a thorough overview of the state-of-the-art, current problems, as well as future trends in virtual reality applications in smart manufacturing. Hopefully, it will offer clues for future work.

4. Threats: For this work, there are some threats, mainly because the virtual reality technologies used in smart manufacturing are not mature enough, the depth of application may be limited by a technological bottleneck, and some predictions of future directions based on the current progress may not be precise.

7. Conclusion

Although this paper reviews recent advances in the application of virtual reality in intelligent manufacturing, there is still a significant need for a natural way to interact with virtual reality in a manufacturing environment. The majority of the applications are still in the research stage rather than the application stage. Furthermore, most applications require an ideal environment instead of the complex environment in the factory. As a result, advanced sensing and computing technology is required to facilitate its popularity in its actual application in the near future. It can be expected that the newly developed sensing technology and interaction solution will make virtual reality much more natural than in the past.

Conflict of interest

The authors declare there is no conflict of interest.

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