

Research on the Impact of Augmented and Virtual Reality Technologies on Production Efficiency in Industrial Manufacturing

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Abstract. In the era of Industry 4.0, traditional manufacturing processes frequently faced efficiency problems in assembly and equipment maintenance due to high loads and suboptimal information transfer. This paper investigated the impact of Augmented Reality (AR) and Virtual Reality (VR) technologies on production efficiency and manufacture. By employing case studies and literature analysis, this research evaluated immersive technology applications across research and development (R&D), production assembly, and remote maintenance phases. The findings revealed that VR accelerated design iterations by enabling high-fidelity virtual prototyping and ergonomic assessments without physical mock-ups. Furthermore, AR significantly reduced operator cognitive load by overlaying real-time, spatially registered instructions onto physical workpieces, effectively eliminating the split-attention effect. AR-enabled remote collaboration also minimizes average repair time by optimizing the remote transfer of expert knowledge. However, the study identified that widespread adoption remained constrained by hardware limitations, visual fatigue, and data synchronization bottlenecks. In conclusion, despite current technical constraints, AR and VR fundamentally optimize human-computer interaction. Future integration with 5G networks and artificial intelligence will resolve existing limitations, thereby maximizing overall manufacturing throughput and lean production capabilities.

Keywords: Augmented Reality (AR), Virtual Reality (VR), Industry 4.0, Production Efficiency, Remote Maintenance, Human-Computer Interaction

1. Introduction

Industries serve as the primary engines of national economic growth and prosperity. By adopting advanced smart technologies, modern manufacturing sectors have seen productivity improved by 17% to 20% [1]. The appliance of advanced smart technologies has fundamentally transformed the manufacturing landscape. By facilitating real-time data exchange across every stage of the product development lifecycle, companies can now achieve greater flexibility. This enables the creation of high-quality products while significantly accelerating their delivery to the market [2]. For the traditional manufacturing processes, bottlenecks in complex assembly, standard operating procedure (SOP) training, and equipment maintenance are the main challenges. Humans possess a restricted

capacity for processing information, while the efficiency of manufacturing systems is consistently on the rise, leading to an escalation in work complexity. While current research highlights the potential of applying advanced smart technologies in factories, there remains a significant research gap regarding the specific human-computer interaction mechanisms that block the integration of digital data streams and physical operations.

This paper investigates the impact of the mechanism of Augmented Reality (AR) and Virtual Reality (VR) technologies on production efficiency in industrial manufacturing. Supported by advanced electronic information systems, AR and VR redefine industrial interfaces by overlaying real-time information onto physical spaces or generating immersive virtual prototypes. Specifically, this study aims to explore how visual and physical interactions in AR/VR environments reduce operator cognitive load, and how variations in information density influence perceptual efficiency.

This research evaluates AR/VR applications across design iteration, assembly operations, and remote maintenance phases. The significance of this study lies in unpacking the underlying mechanisms of spatial computing and immersive technologies that optimize human-machine interaction, thereby enhancing production efficiency and promoting lean manufacturing. The findings will provide theoretical support for optimizing human-machine collaborative systems and offer strategies for implementing AR/VR solutions, thereby accelerating the evolution of intelligent manufacturing.

2. The theory of AR/VR for assisting production

2.1. Psychological perspectives: cognitive load reduction through visual and physical operations

In complex manufacturing environments, traditional instructional media force operators to divide their attention between physical workpieces and detached manuals [5]. According to cognitive load theory, this split-attention effect significantly increases extraneous cognitive load, overwhelming the limited capacity of human working memory [3]. A central premise of cognitive load theory is that human cognitive processing is severely constrained by working memory limitations, which can only process a limited number of information units at any given time. The cognitive load escalates when superfluous demands are placed on the cognitive system. When cognitive load reaches excessive levels, it obstructs both learning and the transfer of knowledge [3]. Augmented Reality (AR) mitigates this psychological bottleneck by directly assisting the informational phase of industrial operations. Instead of forcing operators to spatially frame a task in a presumed mental model and subsequently map its location to the physical world, AR integrates technical documentation directly into the operator's natural field of view(FOV) [4]. This visualization minimizes disruptive visual context switching and physical head movements, as shown in Table 1, thereby significantly reducing task time and error rates [4].

Table 1. Differences of the two assistance modes in terms of the performance and cognitive load of the assembly task

Index	Screen-based documentation assisted group (n = 23)	AR-assisted group (n = 24)	t
Total time (s)	159.641 ± 34.512	131.432 ± 36.761	2.710**
The time for the commissioning subtask (s)	56.143 ± 11.569	46.399 ± 13.561	2.645*
The time for the joining subtask (s)	103.498 ± 29.784	85.033 ± 26.191	2.260*

Table 1. (continued)

Total mistakes	1.780 ± 1.043	0.290 ± 0.624	5.978** *
Mistakes in the commissioning subtask	0.830 ± 0.650	0.210 ± 0.415	4.786** *
Mistakes in the joining subtask	0.960 ± 0.638	5.500 ± 1.588	0.044
Ratings of psychological effort	5.520 ± 1.831	5.500 ± 1.588	0.044
Ratings of task difficulty	4.480 ± 2.042	3.830 ± 1.786	1.154

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

2.2. Immersion and spatial computing: enhancing Standard Operating Procedures (SOPs)

Immersion refers to the extent a technological system presents a highly vivid, spatially organized sensory environment. In the context of industrial Standard Operating Procedures (SOPs), immersive technologies provide critical spatial computing advantages. Virtual Reality (VR) establishes a fully immersive simulation for initial SOP training, enabling operators to develop necessary spatial awareness and muscle memory before entering the actual shop floor [5]. In turn, AR extends this immersive support to physical production by aligning digital twins with real-world equipment. This precise spatial mapping ensures that SOPs are transformed from abstract text into visual guides, thereby ensuring strict compliance with complex assembly sequences.

2.3. Information density and perceptual efficiency: paper/screens vs. overlaid information

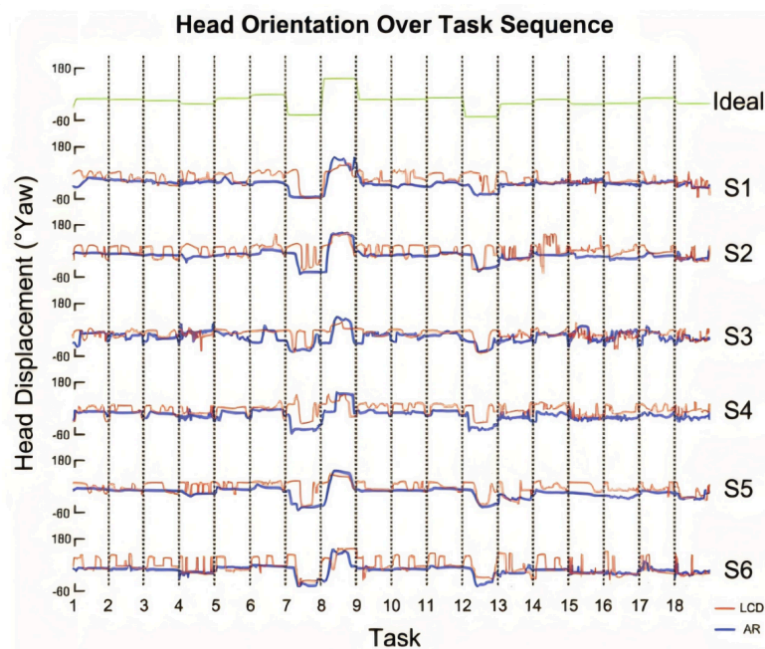


Figure 1. Head orientation (yaw) trajectories for each use under AR and LCD conditions. The X-axis shows normalized elapsed time for each task, and the Y-axis shows rotational head displacement about the forward-facing direction

Modern manufacturing involves reading highly dense information, particularly when assembling complex microelectronic systems or routing digital communication modules. Traditional paper blueprints and 2D screens create a perceptual bottleneck; they present static, uncontextualized data that forces the operator to perform constant mental rotations to map 2D diagrams onto 3D objects. AR and VR optimize information density by applying contextual filtering. Overlaid information is spatially registered, meaning that dynamic, task-relevant data is displayed exclusively at the specific physical coordinates where an action is required [5]. Figure 1 demonstrates that the AR delivery system improves perceptual efficiency by reducing repetitive head movements, outperforming conventional flat-panel displays such as standard LCDs, which suffer from low efficiency in handling information-dense tasks [4].

3. Analysis of the impact of AR/VR on production efficiency

3.1. Research and development and design stage

In the research and development (R&D) phase, Virtual Reality (VR) revolutionizes the design iteration and verification workflow. Traditional prototyping of large-scale industrial equipment frequently requires costly and time-consuming physical fabrication. By applying advanced simulation and rendering engines, engineers can construct high-fidelity virtual prototypes directly from 3D computer-aided design (CAD) blueprints [6]. These virtual environments simulate not only physical geometry but also the operational kinematics and potential ergonomic bottlenecks of the manufacturing equipment. For instance, when designing complex assembly lines, VR allows engineers to ergonomically assess workstation layouts and simulate operator reachability and posture before any physical infrastructure is constructed [6]. This immersive testing facilitates the early identification of design flaws and spatial conflicts. As a result, manufacturers can eliminate multiple rounds of physical prototypes, significantly cutting material waste, reducing trial-and-error costs, and speeding up overall time-to-market [6].

3.2. Production assembly and operation stage

During the production assembly phase, particularly in the integration of intricate mechanical systems and wiring harnesses, Augmented Reality (AR) establishes a multidimensional pathway to enhance the efficiency. First, the real-time overlay of digital instructions onto physical workpieces eliminates the time-consuming process of consulting detached traditional manuals. Operators receive dynamically updated, context-aware visual cues that guide them through complex sequential procedures [7]. For example, when assembling a aircraft engine, AR HMDs project components' spatial coordinates, torque specifications, and fastening sequences directly onto the physical components. This visual guidance prevents the split-attention effect, enabling operators to maintain unbroken focus on the physical manipulation of the hardware. Second, AR systems integrate visual recognition algorithms, depth sensors, and spatial computing to create an active, real-time error correction mechanism. By monitoring the assembly process through integrated camera feeds, the system can instantly detect operational deviations—such as the misalignment of a gear or an incorrect cable connection [8]. When a fault is detected, the AR interface instantly issues visual alerts, stopping errors from spreading to later manufacturing stages. This combination of accelerated information retrieval and preemptive error management significantly maximizes overall assembly throughput [8].

3.3. Maintenance and remote collaboration

Equipment maintenance is a time-sensitive operation in manufacturing, where machine downtime directly leads to significant economic losses. AR technologies drive a paradigm shift in maintenance workflows through advanced remote collaboration capabilities. When unexpected failures occur in key production equipment such as industrial robotic arms or Computer Numerical Control (CNC) machines, on-site technicians can stream their real-time, low-latency field of view to remote experts. This can significantly lower maintenance costs and improve efficiency [9]. The video stream is often enhanced with spatial mapping data, enabling remote experts to grasp the precise physical context of the faulty equipment. Through dedicated AR interfaces, experts can project precise annotations, complex mechanical schematics, and targeted diagnostic points directly into the on-site technician's field of view [4]. For example, when technicians are instructed to remove or install fasteners, animated visualizations demonstrate the correct tool movements required to complete the task [4]. This spatially anchored remote guidance overcomes the geographical and temporal barriers of dispatching specialists to the production site. Ultimately, this smooth transfer of expert knowledge substantially shortens average repair time, optimizes information transmission, and minimizes equipment downtime, thereby sustaining stable production efficiency [9]. Using HMD technology, complex maintenance time for a motor engine can be reduced by 79%, and the error rate can be cut by up to 92.4% [9].

4. Technical limitations of AR/VR in manufacturing applications

4.1. Hardware constraints in latency, battery life, and Field of View (FOV)

Despite significant advancements in spatial computing, current Augmented Reality (AR) and Virtual Reality (VR) head-mounted displays (HMDs) face substantial hardware constraints that restrict industrial application. A primary physical limitation is the restricted Field of View (FOV), which typically ranges between 30 to 50 degrees for optical see-through AR devices [10]. This narrow FOV forces operators to constantly perform unnatural head movements to scan the augmented environment, thereby negating some of the ergonomic benefits of immersive interfaces. Furthermore, untethered HMDs suffer from severely restricted battery life. Running complex spatial tracking and high-resolution rendering simultaneously drains power quickly. Since the launch of the Apple Vision Pro, this flagship HMD only provides up to three hours of video playback [10]. Additionally, system latency, the delay between physical user movement and visual display update—must be kept strictly below 20 milliseconds to maintain immersion. However, current mobile processing units embedded in wireless HMDs frequently struggle to sustain this threshold during processing information from the camera [9].

4.2. Psychological and physiological factors: visual fatigue and motion sickness

The widespread adoption of immersive technologies is further hindered by profound physiological challenges, most notably visual fatigue and cybersickness. Visual fatigue in AR and VR environments stems mainly from the vergence-accommodation conflict. Current optical engines project images at a fixed focal distance, while the human eye naturally attempts to converge and accommodate virtual objects at varying apparent depths. This continuous neurological decoupling leads to severe ocular muscle strain, headaches, and blurred vision after prolonged use [12]. Meanwhile, motion sickness (cybersickness) arises from sensory conflicts between the visual input

from the HMD and the vestibular system's perception of physical movement [12]. High display latency, rendering delays, and suboptimal refresh rates worsen these sensory conflicts. In high-risk manufacturing settings, these symptoms—including dizziness, nausea, and spatial disorientation—seriously threaten operator safety and sharply reduce task concentration [12].

4.3. Data integration and synchronization: data bandwidth and update time implementing

AR/VR systems in modern intelligent manufacturing necessitate the real-time integration of massive data streams from Industrial Internet of Things (IIoT) sensors and digital twin models. This requirement exposes critical limitations in data bandwidth and supporting infrastructure. Rendering high-quality virtual prototypes or dynamic operational data onto physical machinery requires gigabit-level wireless bandwidth and ultra-low latency networks [13]. Insufficient network infrastructure leads to asynchronous data updates, in which overlaid digital instructions or diagnostic parameters lag behind the actual physical state of production equipment [13]. Such synchronization failures not only disrupt operational workflows but also cause catastrophic assembly errors when real-time safety parameters—such as critical torque values or temperature readings—are delayed or out of sync. Therefore, until advanced localized edge computing networks and 5G infrastructure are widely implemented on factory floors, data transfer bottlenecks will remain a major barrier to AR/VR integration [13].

5. Conclusion

This study investigates the mechanisms and impact of Augmented Reality (AR) and Virtual Reality (VR) technologies on production efficiency by transforming digital data into visual guidance. In the research and development (R&D) phase, VR accelerates design iteration cycles and reduces physical prototyping costs via high-fidelity simulation. During the production and assembly stages, AR mitigates the split-attention effect and reduces extraneous cognitive load by overlaying real-time, context-aware instructions directly onto physical workpieces, while its active error-correction mechanism minimizes defect rate. For equipment maintenance, AR-enabled remote collaboration breaks geographical barriers, allowing experts to project precise diagnostic guidance into the local technician's view. This spatial knowledge transfer substantially decreases the average repair time and minimizes equipment downtime. Overall, AR and VR technologies transition industrial operations from recall-based execution to recognition-based processes, thereby serving as critical technical enablers for achieving lean production in Industry 4.0.

Looking forward, the widespread industrial integration of AR and VR will depend on overcoming current network and hardware limitation. The deployment of 5G network and edge computing infrastructure will resolve existing data bandwidth bottlenecks [13]. The infrastructure will enable the real-time synchronization of massive data streams between physical machinery [14]. Moreover, the convergence of artificial intelligence (AI) with immersive technologies represents a transformative future trend. Autonomous AI agents and advanced machine learning algorithms will likely be integrated into AR systems to provide predictive maintenance alerts and dynamically generate context-specific assembly instructions based on real-time operational data [14]. The hardware advancement such as expanded FOV, extended battery life and improved optics will eventually eradicate visual fatigue and motion sickness. Ultimately, as these synergistic technologies mature, Industry 4.0 will evolve from a conceptual framework into a widespread operational standard, continuously redefining global manufacturing efficiency.

References

- [1] Phuyal, S., Bista, D., & Bista, R. (2020). Challenges, opportunities and future directions of smart manufacturing: A state of art review. *Sustainable Futures*, 2, 100023. <https://doi.org/10.1016/j.sfr.2020.100023>
- [2] Eswaran, M., & Bahubalendruni, M. V. A. R. (2022). Challenges and opportunities on AR/VR technologies for manufacturing systems in the context of industry 4.0: A state of the art review. *Journal of Manufacturing Systems*, 65, 260–278. <https://doi.org/10.1016/j.jmsy.2022.09.016>
- [3] Yang, Z., Shi, J., Jiang, W., Sui, Y., Wu, Y., Ma, S., Kang, C., & Li, H. (2019). Influences of augmented reality assistance on performance and cognitive loads in different stages of assembly task. *Frontiers in Psychology*, 10, 1703. <https://doi.org/10.3389/fpsyg.2019.01703>
- [4] Henderson, S., & Feiner, S. (2011). Exploring the benefits of augmented reality documentation for maintenance and repair. *IEEE Transactions on Visualization and Computer Graphics*, 17, 1355–1368.
- [5] Gavish, N., Gutiérrez, T., & Webel, S. (2015). Evaluating virtual reality and augmented reality training for industrial maintenance and assembly tasks. *Interactive Learning Environments*, 23, 778–798.
- [6] Caputo, F., Greco, A., D'Amato, E., Notaro, I., & Spada, S. (2018). On the use of virtual reality for human-centered workplace design. *Procedia Structural Integrity*, 8, 297–308. <https://doi.org/10.1016/j.prostr.2017.12.031>.
- [7] Wang, X., et al. (2024). Gest-SAR: A spatial AR system for interactive manual assembly guidance with real-time operational feedback. *Sensors*, 24, 658–670.
- [8] Smith, J., et al. (2024). Error management and real-time correction for augmented reality assembly instructions. *IEEE Trans. Vis. Comput. Graph.*, 30, 120–134.
- [9] Palmarini, R., Erkoyuncu, J. A., Roy, R., et al. (2018). A systematic review of augmented reality applications in maintenance. *Robotics and Computer-Integrated Manufacturing*, 49, 219–228.
- [10] Apple. (2024). Apple Vision Pro. Apple. <https://www.apple.com/apple-vision-pro/>
- [11] Xiong, J., Hsiang, E. L., He, Z., Wu, T., & Wu, S. T. (2021). Augmented reality and virtual reality displays: Emerging technologies and future perspectives. *Light Science & Applications*, 10, 1–30.
- [12] Saredakis, D., Szpak, A., Adams, B., et al. (2020). Factors associated with virtual reality sickness in head-mounted displays: A systematic review and meta-analysis. *Frontiers in Human Neuroscience*, 14, 1–13.
- [13] Siriwardhana, Y., Porambage, P., Liyanage, M., & Ylianttila, M. (2021). A survey on mobile augmented reality with 5G mobile edge computing: Architectures, applications, and technical aspects. *IEEE Communications Surveys & Tutorials*, 23, 1160–1192.
- [14] Tao, F., Qi, Q., Wang, L., & Nee, A. Y. C. (2019). Digital twins and cyber-physical systems toward smart manufacturing and industry 4.0: Correlation and comparison. *Engineering*, 5, 653–661.