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Generative artificial intelligence of things systems, multisensory immersive extended reality technologies, and algorithmic big data simulation and modelling tools in digital twin industrial metaverse

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Keywords: generative artificial intelligence of things; multisensory immersive extended reality; big data; digital twin; industrial metaverse

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Abstract

Research background: Multi-modal synthetic data fusion and analysis, simulation and modelling technologies, and virtual environmental and location sensors shape the industrial metaverse. Visual digital twins, smart manufacturing and sensory data mining techniques, 3D digital twin simulation modelling and predictive maintenance tools, big data and mobile location analytics, and cloud-connected and spatial computing devices further immersive virtual spaces, decentralized 3D digital worlds, synthetic reality spaces, and the industrial metaverse.

Purpose of the article: We aim to show that big data computing and extended cognitive systems, 3D computer vision-based production and cognitive neuro-engineering technologies, and synthetic data interoperability improve artificial intelligence-based digital twin industrial metaverse and hyper-immersive simulated environments. Geolocation data mining and tracking tools, image processing computational and robot motion algorithms, and digital twin and virtual immersive technologies shape the economic and business management of extended reality environments and the industrial metaverse.


Findings & value added: Simulated augmented reality and multi-sensory tracking technologies, explainable artificial intelligence-based decision support and cloud-based robotic cooperation systems, and ambient intelligence and deep learning-based predictive analytics modelling tools are instrumental in augmented reality environments and in the industrial metaverse. The economic and business management of the industrial metaverse necessitates connected enterprise production and big data computing systems, simulation and modelling technologies, and virtual reality-embedded digital twins.

Introduction

Ambient sound recognition software, virtual modelling and image-based visual computing technologies, and asset maintenance simulations configure the metaverse decentralized infrastructure and 3D computer-generated virtual environments. Cognitive modelling and virtual immersive technologies, Internet of Things-based decision support and haptic augmented reality systems, and mobile location and geospatial big data analytics articulate blockchain-based virtual worlds and the industrial metaverse. Brain-inspired cognitive and visual perceptive systems, immersive and interactive technologies, and 3D image modelling and machine vision tools assist
interoperable extended reality environments and decentralized 3D digital worlds.

Business and economic applications reveal that metaverse, immersive, and virtual and augmented reality technologies can be harnessed in task assembly performance and artificial intelligence (AI)-powered predictive maintenance by factory-level employees in smart Internet of Things manufacturing and automation through flexible workforce training and up-skilling in terms of quality control, interactive data analysis, and real-world scenario simulation, driving team productivity.

Previous literature has indicated that wearable augmented and virtual reality devices, Web3 and machine intelligence technologies, and digital twin simulation and 3D image modelling tools (Balaska et al., 2023; Hou et al., 2024; Jagatheesaperumal & Rahouti, 2022) enable immersive virtual environments. Metaverse decentralized governance and machine learning-based decision support systems, deep learning-based ambient sound processing and synthetic data tools, and digital twin and 3D immersive virtual reality technologies further digitally-networked mediated spaces. Multi-modal synthetic data fusion and analysis, simulation and modelling technologies, and virtual environmental and location sensors shape the industrial metaverse.

Our systematic review clarifies that virtual modelling and simulation tools, photorealistic synthetic images and data, and context-aware augmented reality and visual sensor systems (Alimam et al., 2023; Ji et al., 2023; Negri & Abdel-Aty, 2023) optimize immersive industrial metaverse. In terms of business and economic relevance, edge AI sensing and machine vision systems, cloud and edge computing technologies, and industrial automation tools can handle smart manufacturing data across production environments in terms of edge infrastructure management, driving business value creation and achieving sustainable innovation by enterprise service augmentation and automation.

Virtual reality-based visual perception and remote sensing technologies, metaverse economic and virtual production process systems, and visual, optical, and acoustic sensors enhance immersive decentralized 3D digital worlds and collaborative 3D design environments. The research problem of the systematic review was whether big data computing and extended cognitive systems, 3D computer vision-based production and cognitive neuro-engineering technologies, and synthetic data interoperabil-
ity improve artificial intelligence-based digital twin industrial metaverse and hyper-immersive simulated environments.

The business value of modular, scalable, and flexible generative AI systems, manufacturing operation and factory automation control technologies, and cloud computing services is that they can manage industrial data by virtual staff, driving operational changes and fostering skill building-based team innovation and collaborative work environments.

Bibliometric and visualization analysis is carried out to clarify that Industrial IoT and manufacturing automation technologies, machine learning and data processing algorithms, and management collaboration tools can harness problem-solving skill-based operational expertise for organizational innovation and performance across highly-realistic shop floor simulation environments.

Multi-sensory extended reality and digital scent technologies, deep reinforcement learning-based and visual object tracking algorithms, and autonomous cognitive and neuromorphic computing systems (Mourtzis et al., 2024; Wu et al., 2023; Yang et al., 2022) can be deployed in decentralized 3D digital worlds. Internet of digital twins, photorealistic synthetic images and data, cloud virtual machines, and virtual plant floor networks can be leveraged in immersive and interoperable spaces. 3D simulation spaces develop on digital twin data modelling and visualization tools, big data computing and geo-distributed autonomous intelligent systems, and swarm robotic and path planning algorithms.

Our research gap diagnosis indicates that this is the first paper showing that digital twin and deep learning generative AI technologies, product development and natural language processing tools, and Internet of Things cloud computing and autonomous navigation systems enable data synthesis augmentation and value creation in smart manufacturing operations across process- and forecast-driven production environments. While previous analyses on the topic (e.g., Lăzăroiu et al., 2022; Lăzăroiu et al., 2023; Lewandowska et al., 2023) only highlighted that AI digital twins, equipment sensor data analysis, and intuitive reasoning pattern recognition can decrease operational downtime, augment and streamline equipment reliability and staff productivity, and interactive operational performance, fostering employee happiness, we contribute to the literature by pointing out that immersive collaborative industrial generative AI and remote sensing technologies, cloud-based factory simulation and virtual reality systems, and data collection mapping and obstacle detection tools in modular robot-
ic and machine automation factories can build essential problem-solving and product design skills with regard to autonomous navigation collision avoiding tasks, incorporate multi-modal data across IoT collaborative sensing networks, and scale up innovation processes and robotic manufacturing productivity by environmental monitoring.

The sections of the manuscript: With regard to the literature review, we clarify that generative AI digital twin-based algorithmic organizational behaviors and collective decision making, computation-intensive machine learning techniques, and data cooperatives can improve the multiscale dynamics of social communication and autonomous problem-solving across manufacturing supply chains and cloud computing infrastructures. We then explain the systematic review screening software tools and evidence synthesis technologies deployed as part of methodology.

The source correlation analysis illustrates that digital twin factories in the virtual environment of the metaverse develop on machine intelligence and mobile edge computing technologies, deep learning-based ambient sound processing and virtual 3D scene simulation tools, and semantic 3D mapping and spatial cognition algorithms. Industrial extended reality and digital twin technologies, edge computing and decision-making process automation tools, and spatial cognition and visual perception algorithms can be deployed in 3D digital environments and in edge artificial intelligence-based metaverse architectures. Metaverse and digital twin technologies, multi-sensor fusion and multimodal generative artificial intelligence systems, and computer vision and robot motion algorithms can be harnessed in intelligent simulation environments and immersive 3D worlds.

We then debate on immersive hyper-connected virtual spaces in the industrial metaverse in relation to 3D digital twin and predictive modelling techniques, haptic object recognition and synthetic data-based autonomous production systems, and deep reinforcement learning and computer vision algorithms. The conclusions and specific contributions to the literature summarize and develop on digital twin-enabled industrial Internet of Things in terms of computer vision artificial intelligence and synthetic media-based automated production systems, robotic sensing and multisensory data fusion technologies, and 6G-enabled edge artificial intelligence and virtual 3D scene simulation tools. Limitations, further directions of research, and practical implications analyze artificial intelligence-based digital twin industrial metaverse with regard to virtual plant floor and distributed sensor networks, swarm robot autonomous navigation and
data-driven algorithmic technologies, and deep learning image segmentation and machine learning algorithms.

**Literature review**

Geospatial mapping and edge computing tools, autonomous cognitive and interactive 3D geo-visualization systems, and 3D computer vision-based production and motion capture technologies (Agarwal & Alathur, 2023; Mourtzis *et al.*, 2023a; Wang *et al.*, 2023a) can be harnessed in the metaverse interactive environment. Virtual reality-embedded digital twins, cognitive and behavioral technologies, and machine vision and 3D virtual space networking tools (Calandra *et al.*, 2024; Ooi *et al.*, 2023; Ying *et al.*, 2023) can be deployed in synthetic digitally-mediated environments. Digital twin-based virtual sensors, geolocation data mining and tracking tools, and cloud-based industrial automation and synthetic intelligence technologies can be leveraged in the Internet of Things-based industrial environments.

The economic and business management of immersive augmented and virtual reality technologies and large-scale coordinated generative AI digital twin interoperable governance structures and practices shape organizational changes, job turnover, and skills-based hiring processes and procedures. Generative AI enterprise data, virtual machines, and machine learning systems can drive operational productivity and business value, augment staff decision-making, and maximize employee efficiency by workforce management optimization, tailored data analyses, and streamlined and intuitive business process reengineering tools.

Photorealistic virtual reality environments and the industrial metaverse (Jagatheesaperumal *et al.*, 2023; Mourtzis *et al.*, 2023b; Wang *et al.*, 2023b) develop on spatio–temporal fusion and path planning algorithms, remote assistance and deep learning-based ambient sound processing tools, and edge computing and motion capture technologies. Synthetic digitally-mediated environments (Camacho-Muñoz *et al.*, 2023; Özkal *et al.*, 2024; Zaidan *et al.*, 2023) integrate Internet of Things-based decision support and neuromorphic computing systems, cloud-based object tracking and big data processing tools, and 3D virtual scanning and edge computing technologies. Metaverse interactive environments require bio-inspired artificial vision and Internet of Things-based sensing systems, photorealistic synthetic images and data, and hyper-realistic immersive 3D simulations.
Immersive and interactive virtual environments (Bellalouna & Puljiz, 2023; Han et al., 2023a; Xuhong & Xuan, 2023) necessitate virtual 3D scene simulation and empathetic computing systems, wearable Internet of Things and interconnected virtual devices, and edge artificial intelligence-based infrastructure virtualization and deep reinforcement learning tools. Visual object tracking and machine learning algorithms, digital twin simulation and virtual navigation tools, and dynamic routing and data mining technologies (Chang et al., 2022; Rejeb et al., 2023; Zhang et al., 2023) are pivotal in ambient sensing environments and in the blockchain-based metaverse. Simulated augmented reality and multi-sensory tracking technologies, explainable artificial intelligence-based decision support and autonomous cognitive systems, and ambient intelligence and deep learning-based predictive analytics modelling tools are instrumental in augmented reality environments and in the industrial metaverse.

Business and economic applications reveal that generative AI can improve productivity by data mining techniques, increasing economic growth, while simultaneously leading to improved employee engagement, enthusiasm, commitment, and satisfaction, reduced stress and burnout, and effective working relationships, and to diminished motivation, massive job displacement, elevated turnover rates, and real wage decrease. Generative AI can develop cohesive team dynamics, employee empowerment, well-being, autonomy, and engagement, positive organizational culture, and supportive work environments, providing adequate support, building adaptable workforce, attracting high-quality talent, reshaping job roles effectively, fostering a goal-oriented staff in terms of creativity and initiative, and reducing inequity perceptions and team member conflicts, resulting in elevated productivity and innovation.

Immersive 3D worlds (Cao et al., 2023; Kaarlela et al., 2023a; Park et al., 2023) integrate digital twin modelling and real-time object detection tools, machine vision and environment mapping algorithms, and vision-based robotic sensing and data mining techniques. 3D modelling environments (Ferrigno et al., 2023; Lyu & Fridenfalk, 2023; Tan et al., 2023) require Internet of Robotic Things systems and devices, computational cognitive modelling and sensory-based robot control tools, digital twin industrial and bio-inspired soft robots, and visual perception and swarm robotic algorithms. Visual situational awareness environments necessitate metaverse and digital twin technologies, 3D simulation and operational modelling tools, and multi-sensor fusion and collaborative autonomous systems.
Internet of Things sensors, deep learning-based sensing and digital twin technologies, and virtual simulation and machine learning clustering algorithms (Chai et al., 2023a; Kaarlela et al., 2023b; Yu et al., 2023) are pivotal in 3D digital environments. Asset maintenance simulations, cognitive modelling and virtual immersive technologies, and wearable Internet of Things and virtual reality devices (Fu et al., 2023; Ma et al., 2023; Theodoropoulos et al., 2023) configure decentralized 3D digital worlds. Motion capture and dynamic routing technologies, ambient sound recognition software, and location-aware networked and empathetic computing systems articulate photorealistic virtual reality environments.

The economic and business management of 3D mapping technologies, augmented reality algorithms, and holographic displays can enhance inconsistent resources, workforce planning and immersive experiences, reshape supply chains, transform warehousing operations, and tailor communications by networked data capturing and measuring for talent pools across virtual collaborative environments. Generative AI algorithms and augmented reality technologies can streamline decision-making processes in relation to growing workloads across networked device collaboration system interoperability and space planning, configuring immersive supply chain, real-time performance feedback and simulation, and logistics training experiences.

Methods

The systematic review screening software tools and evidence synthesis technologies deployed were AMSTAR (for methodological quality evaluation), BIBOT (for article retrieval and analysis by machine learning techniques), CASP (for qualitative evidence identification, evaluation, and synthesis in finding support and validation), Catchii (for duplicate record detection and removal, automatic querying, and full-text analysis), R package and Shiny app citationchaser (for research article connection identification and explicit mentioning beyond complex search string-based bibliographic database searching, and for backward and forward citation mining and tracking and reference scanning, harvesting, and checking by use of machine learning screening algorithms), DistillerSR (for data extraction, output, screening, management, and tracking by use of artificial intelligence workflows), JBI SUMARI (for study selection, data extraction and synthe-
sis, and critical appraisal, in terms of plausibility, suitability, significance, and effectiveness, and bias identification associated with evaluation, detection, and measurement of published results), Litstream (for literature screening, transparent documentation, data extraction collaboration, and duplicate and redundancy removal), Nested Knowledge (for data screening and extraction, and result visualization and analysis), Rayyan (for term tagging, selection, screening, deduplication, and highlighting in relevant study identification), and Systematic Review Accelerator (with tools such as Methods Wizard, Word Frequency Analyser, Search Refinery, Deduplicator, Screenatron, and Disputatron harnessed for common word and phrase identification, unnecessary term removal, search string duplicate exclusion, and abstract screening disagreement detection).

The search period was April 2024, and the search terms were “digital twin industrial metaverse” + “artificial Intelligence of Things systems”, “multisensory immersive extended reality technologies”, and “algorithmic big data simulation and modelling tools”. The selected sources were 114 out of 336 (Table 1). The published research inspected was between 2022 and 2024. PRISMA was the reporting quality assessment tool (Figure 1), while Dimensions and VOSviewer were deployed as data visualization tools (Figures 2–5). Our research approach, by integrating complex screening software tools and evidence synthesis technologies, aims to identify the most relevant sources for our analysis, while speeding up the selection process.

Results

Source correlation analysis

Co-authorship correlations (Figure 2) show that cognitive digital twin and virtual reality technologies, artificial intelligence-powered visual sensors, and geolocation tracking and 3D simulation tools further immersive virtual spaces. Sensory data mining and distributed artificial intelligence techniques, real-time remote control, and realistic 3D digital twins shape virtual machines and factories. 3D digital twin and sensory data mining techniques, industrial data semantics, and deep generative modelling and digital twin simulation tools optimize the digital asset-based virtual economy. Multimodal generative artificial intelligence and location-aware networked
systems, computer graphics-based photorealistic imagery, and situational awareness and predictive maintenance algorithms can be harnessed in immersive 3D worlds. Realistic 3D digital twins, collaborative intelligence and context modelling tools, and semantic 3D mapping and predictive maintenance algorithms can be deployed in immersive hyper-connected virtual spaces. Extensive data analysis-based decision-making processes, equipment failure prediction, process digitization and automation, cognitive computing-based biologically-inspired distributed intelligence, and maintenance schedule optimization can reduce machine downtime and maintenance.

Citation correlations (Figure 3) show that artificial intelligence-powered visual sensors, metaverse and digital twin technologies, and cyber-physical production and context-aware augmented reality systems can be leveraged in virtual machines and factories. Interconnected virtual worlds develop on perception-based reinforcement learning tasks, multiple autonomous mobile robots, and dynamic routing and data mining technologies. Immersive virtual spaces integrate wearable haptic garments, deep learning-based image processing and artificial intelligence-driven computer vision algorithms, and dynamic routing and cloud-based cognitive technologies. Extended reality environments require location-aware networked and computer vision artificial intelligence systems, industrial 5G and wireless visual sensor networks, and connected machines and objects. Predictive and generative cognitively-inspired visual artificial intelligence holographic imaging and machine vision technologies, visual data processing and geolocation data tools, and wearable physiological sensing and spatial computing devices articulate multi-sensory visually stimulating environments. Decision-making and workflow simulation and automation develop on Internet of Things device remote and machine performance monitoring tools, industrial digital twins, and spatial computing and machine vision technologies in generative artificial intelligence-based product management and engineering.

Bibliographic coupling correlations (Figure 4) show that interactive and immersive technologies, bio-inspired computation and ambient intelligence tools, and connected Internet of Things digital twins and sensors assist industrial and manufacturing operations. Real-time digital twin-based asset, device, and process monitoring can improve operational efficiency and streamline data-driven decision-making across measurement devices and industrial control systems on the factory floor. Semantic-aware naviga-
tion and predictive maintenance software tools, Internet of Things digital twins, and simulation digital twin and explainable artificial intelligence technologies enable smart data-driven enterprise management and governance. 3D obstacle detection mapping and synthetic computer vision algorithms, Industrial Internet of Digital Twins, and navigation planning and scene perception tools further cognitive intelligence-enabled manufacturing. Deep and machine learning-based sustainable power management systems, production equipment assessment and monitoring tools, and generative artificial intelligence and industrial data analytics shape cognitive manufacturing networks. Interactive 3D environments integrate 3D artificial intelligence computer vision localization and deep learning-based object detection systems, sensor data-based condition and real-time visual analysis, and artificial intelligence edge and neuromorphic computing algorithms for industrial autonomous mobile robots.

Co-citation correlations (Figure 5) show that artificial intelligence-enhanced industrial automation and modular production systems, cognitive digital twin and virtual manufacturing technologies, and remote sensing images optimize enterprise generative artificial intelligence. Cloud-managed cameras and environmental sensors, Internet of Things-based decision support and deep learning-based 3D object detection systems, and artificial intelligence-driven computer vision and visual recognition technologies can be harnessed in industrial metaverse. Machine intelligence and collaborative industrial robotic technologies, artificial cognitive computing and spatial computing algorithms, and object detection and classification tools can be deployed in Industrial Internet of Things-enabled cognitive manufacturing. Brain-inspired computing pattern recognition and maintenance prediction and scheduling tools, machine intelligence and vision algorithms, and 3D augmented reality and distributed ledger technologies can be leveraged in cognitive industrial Internet of Things and cyber-physical production systems. Generative artificial intelligence algorithms can automate and streamline enterprise and business tasks by use of manufactured product real-time data tracking, decision and process automation, operational risk reduction, industrial Internet of Things connected devices and sensors, and diagnostic and predictive capabilities based on cloud-based remote monitoring and diagnostic strengths.
Digital twin factories in the virtual environment of the metaverse: Machine intelligence and mobile edge computing technologies, deep learning-based ambient sound processing and virtual 3D scene simulation tools, and semantic 3D mapping and spatial cognition algorithms

Physics-based modelling and simulation tools, visual perception and neural network-based recognition algorithms, and cloud and edge computing technologies (Chen et al., 2023a; Koohang et al., 2023; Ritterbusch & Teichmann, 2023) configure photorealistic virtual reality and intelligent simulation environments. Machine intelligence and mobile edge computing technologies, wearable augmented and virtual reality devices, and ambient sound recognition software articulate the virtual environment of the metaverse. Neural machine and mobile edge computing networks, machine learning-based decision support and collaborative autonomous robotic systems, and spatial computing and 3D immersive virtual reality technologies assist the metaverse decentralized infrastructure.

Immersive and interactive technologies, realistic virtual simulation and image processing tools, and visual tracking and remote sensing algorithms (Chen et al., 2023b; Kshetri, 2023a; Salam et al., 2023) enable digital twin factories in the virtual environment of the metaverse. Visual digital twins, sensory data mining and 3D imaging techniques, 3D digital twin simulation modelling tools, mobile location and machine learning data analytics, and spatial computing and swarm robotic devices further immersive virtual spaces, decentralized 3D digital worlds, synthetic reality spaces, and the industrial metaverse. Internet of Things-based process and production planning tools, computer vision and object recognition algorithms, and digital twin-enabled edge and industrial artificial Internet of Things networks configure extended reality environments.

Scene recognition and motion capture technologies, deep learning-based ambient sound processing and virtual 3D scene simulation tools, and mobile robotic vision and cloud-edge computing systems (Chen et al., 2023c; Kshetri, 2023b; Schmitt, 2023) articulate immersive photorealistic virtual spaces in the industrial metaverse. Swarm computing and robot control algorithms, remote assistance and big data processing tools, and edge computing and cognitive modelling technologies assist digitally-networked mediated spaces and immersive 3D worlds. Realistic product visualization and edge computing tools, connected enterprise production and automatic process control systems, and multi-sensory stimulation and
robotic motion planning algorithms enable digital twin factories in blockchain-based virtual worlds.

Wearable augmented and biometric self-authentication devices, cloud computing machines, and voice recognition software (Chai et al., 2023b; Kaigom, 2024; Zeng et al., 2023) assist metaverse virtual services in 3D digital environments. Computer graphics-based photorealistic imagery, immersive and interactive technologies, and artificial intelligence-powered search capabilities enable digitally-networked mediated spaces. Image-based visual computing and 3D immersive virtual reality technologies, semantic 3D mapping and spatial cognition algorithms, and semantic-aware navigation and deep learning-based ambient sound processing tools further immersive 3D worlds.

Immersive virtual spaces (Chen et al., 2023d; Laviola et al., 2022; Semeraro et al., 2023) integrate photorealistic synthetic imagery, real-time remote assistance, and multi-digital twin cooperation and big data processing tools. Immersive and interactive virtual environments require deep learning-assisted digital twins, edge computing and immersive holographic imaging technologies, and Internet of Things sensor and neural machine networks. The industrial metaverse necessitates connected enterprise production and big data computing systems, simulation and modelling technologies, and virtual reality-embedded digital twins.

*Industrial extended reality and digital twin technologies, edge computing and decision-making process automation tools, and spatial cognition and visual perception algorithms in 3D digital environments and in edge artificial intelligence-based metaverse architectures*

Industrial extended reality and vision sensing technologies, blockchain-based digital asset management and empathetic computing systems, and geospatial mapping and simulation modelling tools (Chowdhury, 2023a; Lee & Kundu, 2022; Siriweera & Naruse, 2023) further immersive and interactive virtual environments. Geolocation data mining and tracking tools, image processing computational and robot motion algorithms, and digital twin and virtual immersive technologies shape extended reality environments and the industrial metaverse. Machine vision and path planning algorithms, metaverse and digital twin technologies, and interoperable virtual and neural machine networks optimize hyper-immersive simulated environments.
Dynamic routing and tactile sensing technologies, haptic augmented reality and mobile robotic manufacturing systems, and industrial data semantics (Chowdhury, 2023b; Leng et al., 2022; Starly et al., 2023) improve immersive virtual spaces. Blockchain-based Industrial Internet of Things, wearable Internet of Things and biometric self-authentication devices, and digital twin data modelling and visualization tools enhance immersive 3D worlds. Mobile edge cloud-based industrial Internet of Things, physics-based modelling and simulation tools, and brain-inspired cognitive and location-aware networked systems can be harnessed in 3D digital environments and in edge artificial intelligence-based metaverse architectures.

Artificial intelligence-based Industrial Internet of Things, deep learning-based image processing and situational awareness algorithms, and simulation and modelling technologies (Cui et al., 2023; Li et al., 2023a; Stary, 2023) can be deployed in extended reality environments. Cloud-based cognitive and data mining technologies, edge artificial intelligence-based infrastructure virtualization and virtual mapping tools, and photorealistic synthetic imagery can be leveraged in immersive 3D worlds. The industrial metaverse develop on 3D digital twin and sensory data mining techniques, visual perception and spatio-temporal fusion algorithms, and real-time remote assistance and control.

Edge computing and decision-making process automation tools, spatial cognition and visual perception algorithms, and perception-based reinforcement learning tasks (Dolgui & Ivanov, 2023; Li et al., 2023b; Stavroulakis et al., 2022) shape simulated machines and factories. Internet of Things-based decision support and cyber-physical production systems, 3D virtual reality simulation and data processing tools, and semantic network representations optimize hyper-realistic 3D worlds. Artificial intelligence-powered prediction and machine vision tools, virtual twin and digital contact tracing technologies, and brain-inspired cognitive and immersive visualization systems can be harnessed in the industrial metaverse.

Mobile robotic manufacturing and haptic object recognition systems, digital twin-enabled edge and interoperable virtual networks, and sensory data mining and virtual twinning techniques (Erman & Martino, 2023; Li et al., 2023c; Stodt et al., 2023) are pivotal in interconnected digital realms. Edge computing blockchains, ambient environment monitoring sensors, and spatio-temporal fusion and artificial intelligence-driven computer vision algorithms are instrumental in digital twin factories. 3D image modelling and virtual navigation tools, deep reinforcement learning and comput-
er vision algorithms, and mobile location and big geospatial data analytics configure artificial intelligence-based digital twin industrial metaverse.

Metaverse and digital twin technologies, multi-sensor fusion and multimodal generative artificial intelligence systems, and computer vision and robot motion algorithms in intelligent simulation environments and immersive 3D worlds

Intelligent simulation environments and immersive 3D worlds (Faraboschi et al., 2023; Liu et al., 2023a; Stothard, 2023) integrate real-time data and image processing tools, spatial computing and mobile robotic devices, wearable haptic garments, and digital twin data. Immersive 3D worlds require realistic product visualizations, connected machines and objects, semantic network representations, and industrial digital twins. Interconnected digital realms necessitate behavior modelling and edge computing technologies, synthetic media-based automated production and immersive visualization systems, and 3D modelling and virtual simulation tools.

Internet of Things sensor and interoperable virtual networks, extended reality and remote sensing technologies, and collaborative data analysis and context modelling tools (Ferrari & McKelvey, 2023; Liu et al., 2023b; Striffler & Voigt, 2023) are pivotal in the blockchain-based virtual economy. Digital twin simulation and operational modelling tools, digital twin-enabled edge and virtual plant floor networks, and virtual environmental and location sensors are instrumental in the industrial metaverse. Robotic navigation and tactile sensing technologies, digital twin simulation and computational intelligence tools, and soft biomimetic robotic actuators configure extended reality environments.

Multi-digital twin cooperation and remote assistance tools, mobile robotic manufacturing and immersive visualization systems, and swarm computing and path planning algorithms (Guo et al., 2023; Mourad et al., 2023; Wang et al., 2022a) articulate visual situational awareness environments. Deep generative modelling and multi-digital twin cooperation tools, Internet of Things sensing and intelligent connectivity infrastructures, industrial robotic and automatic process control systems, and virtual simulation and predictive maintenance algorithms configure immersive hyper-connected virtual spaces. Deep generative and virtual twin modelling tools, geospatial big data-driven industrial and decentralized data analytics, and
computer vision and robot motion algorithms articulate 3D design and real-time simulation environments.

Machine vision and geospatial mapping technologies, deep learning-based image processing and predictive maintenance algorithms, and virtual machine remote monitoring and computational intelligence tools (Han et al., 2023b; Mourtzis & Angelopoulos, 2023; Wang et al., 2022b) can be deployed in extended reality environments. Multi-sensor fusion and multimodal generative artificial intelligence systems, image processing computational and machine vision algorithms, and geospatial mapping and synthetic data tools can be leveraged in intelligent simulation environments. Digital twin connected factories develop on virtual plant floor networks, geospatial big data analytics, and behavior modelling and tactile sensing technologies.

Haptic object recognition and computer vision artificial intelligence systems, autonomous robotic swarms, and metaverse and digital twin technologies (Huawei et al., 2023; Qian et al., 2023; Yi et al., 2023) articulate hyper-immersive simulated environments. Ontology-based semantic and 3D digital twin modelling technologies, robotic navigation and geospatial modelling systems, and multiple autonomous mobile robots assist the metaverse decentralized infrastructure. Digital twin simulation and geolocation data mining tools, 3D contextual data, and virtual modelling and machine vision technologies enable the interconnected metaverse.

Discussion

Deep learning-assisted digital twins, fault detection and diagnosis tools, integrated digital–physical workflows, and robotic sensor and artificial neural networks (Khalaj et al., 2023; Reiman et al., 2023; Zhou et al., 2023) shape decentralized 3D virtual spaces across the interconnected metaverse. 3D computer vision-based production and immersive holographic imaging technologies, deep learning-based image processing and spatial cognition algorithms, and multimodal generative artificial intelligence and machine learning-based production planning systems (Ganchev et al., 2023; Magalhães et al., 2022; Tlili et al., 2023) configure immersive hyper-connected virtual spaces in the industrial metaverse. Edge artificial intelligence-based infrastructure virtualization and ambient scene detection tools, robotic navigation and multi-agent system distributed cooperative
control, and semantic 3D mapping and situational awareness algorithms articulate cyber-physical system-based smart manufacturing in the industrial metaverse.

Semantic-aware navigation and predictive maintenance tools, 3D digital twin and predictive modelling techniques, and machine vision and deep learning image segmentation algorithms (Al-Sharafi et al., 2023; Jaimini et al., 2022; Wang et al., 2024) assist robot motion planning and control in artificial intelligence-based digital twin industrial metaverse. Geospatial intelligence and cognitive robotic process automation tools, multi-sensory extended reality and visual computing technologies, and industrial digital twins enable autonomous manufacturing plants in extended reality environments. Deep learning-based sensing and extended reality technologies, interconnected visual and synthetic biometric data, and distributed decision and control algorithms (Gattullo et al., 2022; Maier et al., 2024; Truong et al., 2023) further virtual manufacturing machines in hyper-realistic 3D worlds.

3D modelling and simulation technologies, perception-based reinforcement learning tasks, and cloud virtual machines (Aung et al., 2024; Jamshidi et al., 2023; Nagy et al., 2023) configure immersive and interoperable spaces. Metaverse and digital twin technologies, biomimetic tactile and ambient environment monitoring sensors, and anthropomorphic robotic and networked embedded sensing devices (Gourisetti et al., 2023; Meng et al., 2024; Wan et al., 2022) articulate virtual and simulated machines and factories in synthetic digitally-mediated environments. 3D image and synthesis generation tools, haptic object recognition and synthetic data-based autonomous production systems, and virtual navigation and deep learning-based ambient sound processing tools assist immersive and interactive virtual environments.

Digital twin-enabled edge and mobile sensor networks, autonomous robotic swarms, and virtual twin and semantic-based cognitive technologies (Awan et al., 2023; Nair et al., 2024; Xiang et al., 2024) enable synthetic simulation environments. Multiple autonomous mobile robots, bio-inspired computation and sensory data mining techniques, and deep reinforcement learning and computer vision algorithms (Grieves, 2023; Mosco, 2023; Wan et al., 2023) further immersive photorealistic virtual spaces in Web3-powered metaverse worlds. Image-based object recognition and ontology-based semantic technologies, digital twin simulation and virtual
navigation tools, and 3D contextual and captured image data shape edge artificial intelligence-based metaverse architectures.

Bio-inspired computation and sensory data mining techniques, Internet of Robotic Things-based context-aware and robotic perceptual systems, and event modelling and forecasting tools (Jim et al., 2023; Navarro & Pita, 2023; Xinyi et al., 2023) assist Web3-powered metaverse worlds. 3D computer vision-based production and robotic sensing technologies, Artificial Intelligence of Things devices, and interconnected visual and digital twin data enable immersive 3D metaverse cyberspaces. Multi-sensory data fusion and immersive 3D technologies, extended cognitive and metaverse decentralized governance systems, and fog and edge computing technologies further digital twin connected factories.

3D modelling and simulation technologies, virtual twin-enabled industrial Internet of Things, and distributed decision and control algorithms (Bhattacharya et al., 2023; Hou et al., 2023; Netland et al., 2023) shape synthetic digitally-mediated environments. Cognitive neuro-engineering and multi-sensory tracking technologies, auditory and visual immersion systems, and virtual navigation and digital twin modelling tools optimize immersive hyper-connected virtual spaces. Synthetic data-based autonomous production and immersive visualization systems, digital signal processing and spatio-temporal fusion algorithms, and geospatial mapping and image-based object recognition technologies can be harnessed in immersive and interactive virtual environments.

Conclusions

Synthetic intelligence and machine vision technologies, context modelling and decision-making process automation tools, and computer vision artificial intelligence and synthetic media-based automated production systems optimize extended reality environments. 3D modelling and virtual simulation tools, artificial intelligence-powered visual and biomimetic tactile sensors, and cognitive computing and cloud-based industrial automation technologies can be leveraged in simulated machines and factories across immersive photorealistic virtual spaces. Industrial digital twins, cloud-based cognitive and geospatial mapping technologies, and real-time data and image processing tools can be harnessed across the interconnected metaverse. 6G-enabled edge artificial intelligence and virtual 3D scene
simulation tools, semantic communication and immersive geospatial data visualization technologies, and visual localization and mapping devices can be deployed in the interactive industrial metaverse. Our specific contributions to the literature clarify that extended reality environments develop on 3D digital twin modelling and multi-sensor fusion technologies, data processing and operational modelling tools, and blockchain-based decentralized metaverse and multi-sensor fusion systems. Intelligent simulation environments integrate digital twin-enabled industrial Internet of Things, semantic network representations, and 3D virtual scanning and sentiment recognition technologies.

Limitations, further directions of research, and practical implications

Limitations are correlated with the hotness of the topic, relevant sources being published only since 2022 on, and with the selected databases. Inter-connected digital spaces require virtual plant floor and distributed sensor networks, extended reality and scene recognition technologies, and soft biomimetic robots. Immersive 3D environments in the blockchain-based virtual economy necessitate visual sensing and perception systems, digital signal processing and mobile robot path planning algorithms, and virtual twin modelling and real-time object detection tools.

Future research should investigate how big data computing and haptic feedback systems, machine reasoning and predictive intelligence algorithms, and digital twin data modelling and visualization tools are pivotal in the industrial metaverse. Swarm robot autonomous navigation and data-driven algorithmic technologies, computational cognitive modelling and geospatial intelligence tools, and virtual simulation and machine learning algorithms are instrumental in decentralized 3D digital worlds.

Practical implications are related to how multi-agent intelligent and computational imaging systems, fault detection and diagnosis tools, and robotic sensing and multi-sensory data fusion technologies configure the industrial metaverse. Geospatial modelling and multi-agent system distributed cooperative control, deep learning image segmentation and machine learning algorithms, and situational and context awareness technologies articulate the artificial intelligence-based digital twin industrial metaverse.
References


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Annex

Table 1. Topics and types of scientific products identified and selected

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**Type of paper**

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Note: Some topics overlap.

Figure 1. PRISMA flow diagram describing the search results and screening
**Figure 2.** VOSviewer mapping of artificial Intelligence of Things systems, multisensory immersive extended reality technologies, and algorithmic big data simulation and modelling tools in digital twin industrial metaverse regarding co-authorship

**Figure 3.** VOSviewer mapping of artificial Intelligence of Things systems, multisensory immersive extended reality technologies, and algorithmic big data simulation and modelling tools in digital twin industrial metaverse regarding citation
Figure 4. VOSviewer mapping of artificial Intelligence of Things systems, multisensory immersive extended reality technologies, and algorithmic big data simulation and modelling tools in digital twin industrial metaverse regarding bibliographic coupling

Figure 5. VOSviewer mapping of artificial Intelligence of Things systems, multisensory immersive extended reality technologies, and algorithmic big data simulation and modelling tools in digital twin industrial metaverse regarding co-citation