

## INTERNATIONAL JOURNAL ON INFORMATICS VISUALIZATION

journal homepage: www.joiv.org/index.php/joiv



# Exploring the Industrial Metaverse: Empowering Meta-Operators with Industry 5.0 Principles and XR Technologies

Ali Noori Kareem<sup>a,\*</sup>, M.A.Chyad<sup>b</sup>, Zahraa Dawood Salman Al-Gburi<sup>b</sup>, Husam Hamid Ibrahim<sup>b</sup>, Hussien kadhim sharaf<sup>b</sup>

> <sup>a</sup> Department of Computer Engineering, College of Engineering, University of Diyala, Diyala, Iraq <sup>b</sup> Department of Computer Engineering, Bilad Alrafidain University, Diyala, Iraq Corresponding author: <sup>\*</sup>alinoori@uodiyala.edu.iq

*Abstract*—The term "Metaverse" has recently gained significant attention. It refers to a concept aiming to immerse users in real-time 3D virtual worlds using XR devices like AR/MR glasses and VR headsets. When this idea is applied to industrial settings, it's termed the "Industrial Metaverse," where operators leverage cutting-edge technologies. These technologies align closely with those associated with Industry 4.0, evolving towards Industry 5.0 and prioritizing sustainable and human-centric industrial applications. The Industrial Metaverse stands to benefit from Industry 5.0 principles, emphasizing dynamic content and swift human-to-machine interactions. To facilitate these advancements, this article introduces the concept of the "Meta-Operator," essentially an industrial worker guided by Industry 5.0 principles, engaging with Industrial Metaverse applications and surroundings through advanced XR devices. It also delves into the key technologies supporting this concept: Industrial Metaverse components, the latest XR technologies, and Opportunistic Edge Computing (OEC) for interacting with surrounding IoT/IIoT devices. Furthermore, the paper explores strategies for developing the next generation of Industrial Metaverse applications based on Industry 5.0 principles, such as standardization efforts, integrating AR/MR devices with IoT/IIoT solutions, and advancing communication and software architectures. Emphasis is placed on fostering shared experiences and collaborative protocols. Lastly, the article presents a comprehensive list of potential Industry 5.0 applications for the Industrial Metaverse and research directions. It offers a holistic perspective and practical guidance for developers and researchers venturing into Industrial Metaverse applications.

Keywords-Metaverse; industrial metaverse; XR devices; industry 5.0; meta-operator; IoT devices; collaborative protocols.

Manuscript received 8 Apr. 2024; revised 20 Jul. 2024; accepted 3 Sep. 2024. Date of publication 30 Nov. 2024. International Journal on Informatics Visualization is licensed under a Creative Commons Attribution-Share Alike 4.0 International License.



## I. INTRODUCTION

Extended Reality (XR) technologies, such as Augmented Reality (AR) and Mixed Reality (MR), have undergone significant evolution since their inception in the 1960s [1], [2]. However, it wasn't until the late 90s that notable progress was made, driven by both academic [3] and industrial efforts [4], [5]. This progress has culminated in the widespread adoption of AR and MR in various industrial manufacturing processes [6]-[8], particularly within sectors like automotive manufacturing [9], [10]. Positioned as fundamental components of the Industry 4.0 paradigm [11], [12]. AR and MR have demonstrated their capacity to enhance factory performance [13].

Industry 5.0, an emerging paradigm characterized by the European Commission [14], builds upon the foundation laid by Industry 4.0, emphasizing social fairness and sustainability [15]. Central to Industry 5.0 are three core values:

sustainability, resilience, and human centricity. This paper primarily focuses on the latter, exploring the development of human-centric AR/MR applications. Additionally, it introduces the concept of the Meta-Operator, envisioned as the future operator in Industry 5.0 settings, who leverages advanced AR/MR devices to interact with the Industrial Metaverse [16].

The Industrial Metaverse, akin to Industry 5.0, aims to develop human-centric AR/MR applications, forming a network of real-time rendered 3D virtual worlds tailored to industrial use cases [17]. While still nascent, the Industrial Metaverse is anticipated to have a substantial economic impact, with market projections ranging from \$22 billion to \$540 billion [18].

Despite the growing number of AR/MR solutions, few have been designed with Industry 5.0 and the Industrial Metaverse in mind, limiting shared experiences and realworld manipulation of Internet of Things (IoT) or Industrial Internet of Things (IIoT) objects [19]. This paper addresses this gap by proposing the concept of the Meta-Operator, an Industry 5.0 industrial worker empowered by advanced AR/MR technologies to interact with the Industrial Metaverse[20].

Unlike previous reviews, which often focused on specific topics or industries, this paper takes a holistic approach, exploring the intersection of Industry 5.0, the Industrial Metaverse, and enabling technologies such as Augmented/Mixed Reality, IIoT, Opportunistic Edge Computing, and Digital Twins. It offers several novel contributions, including introducing the Meta-Operator concept, a comparative analysis of AR/MR smart glasses, and exploring AR/MR applications for IoT/IIoT devices.

The rest of the paper is structured as follows: Section I provides background information on Industry 5.0, Section II 3. Advanced Interaction Technologies in Extended Reality (XR) Environments, Section III Leveraging Edge Computing for Enhanced Industrial Metaverse Connectivity, and Section IV present conclusions.

#### II. MATERIALS AND METHOD

Industry 5.0, as advocated by the European Commission, represents a new paradigm aimed at advancing economic growth, industrial development, and societal well-being beyond the achievements of Industry 4.0 [21], [22]. Unlike a mere continuation or replacement of Industry 4.0, Industry 5.0 emerges as a fusion of contemporary European industrial and societal trends, complementing the core objectives of its predecessor. Since its inception in 2011 [23], Industry 4.0 has primarily emphasized industrial digitalization, production efficiency, and flexibility, focusing less on addressing societal concerns such as social equity and environmental sustainability. Consequently, Industry 5.0 redirects the principles of Industry 4.0, urging industrial research and innovation towards a human-centric and environmentally conscious trajectory [24], [25].

The European Commission identifies six pivotal areas crucial for the future technological advancement of the industry [26]. These include personalized human-machine interaction, bio-inspired technologies, digital twins and simulation, data management technologies, Artificial Intelligence (AI), and energy efficiency technologies [27]. XR technologies, particularly relevant to personalized human-machine interaction, play a vital role in facilitating individualized interfaces essential for the Industrial Metaverse, an emerging concept closely aligned with Industry 5.0 objectives [28].

The term 'Metaverse' originates in Neal Stephenson's seminal 1992 novel "Snow Crash." Stephenson's literary creation envisaged a persistent virtual realm permeating human existence, blurring the boundaries between labor, leisure, art, and commerce [29]. Etymologically, 'Metaverse' stems from the Greek prefix 'meta', meaning 'beyond', and the stem 'verse', derived from 'universe', suggesting a realm transcending our own. Despite its captivating concept, the Metaverse lacks a unified definition, allowing industry leaders to shape it to fit their ideologies and capabilities [30]. This lack of consensus underscores the scale and diversity of the opportunity recognized by numerous companies. However, the term is often adopted without a comprehensive understanding, reflecting its evolving nature [31], [32].

Debates surrounding the definition of the Metaverse extend to its core technologies. Questions have arisen about whether Augmented Reality (AR) is integral to the Metaverse or distinct from it [8], [33] (see Figures 1 and 2).



Fig. 1 Traditional Augmented Reality Operators



Fig. 2 Core Technologies and Definitions in the Metaverse Debate

Some view the Metaverse as a decentralized iteration of the current internet, emphasizing user control over systems, data, and virtual goods. The distinction between a 'metaverse' and participatory Extended Reality (XR) environments further complicates its definition [34], [35]. Everyday technologies, such as IoT-based home automation systems enabling XR interaction, exhibit Metaverse-like qualities, blurring the lines between categories. Consequently, the term 'Metaverse'

emerges as a fixture in the ever-evolving technological landscape [36].

The Industrial Metaverse's transformative potential lies in facilitating remote collaboration and enhancing industrial processes' efficiency and effectiveness [37]. From ubiquitous computing to advanced tracking technologies, the Industrial Metaverse offers a multifaceted approach to industrial applications, promising seamless integration of technology with the workforce, generating unprecedented value and insights [38]. The Metaverse represents a massively scaled and interoperable network of real-time rendered 3D virtual worlds. It transcends singular entities or specific industries, with various Metaverses catering to diverse interests [39], [40].

#### III. RESULTS AND DISCUSSION

In the current debate, it is suggested that several Metaverses will coexist and eventually form 'metagalaxies,' which are collections of virtual worlds connected under a single authority. On the other hand, some contend that the Metaverse notion may need to be more optimistic or cohesive [41], as defined by companies, is a technology bubble, unattainable due to its loosely connected nature. Platforms like Second Life, Fortnite, Minecraft, or Roblox offer glimpses into the integration of Metaverse features within collaborative applications [42]. Yet, these platforms operate as isolated universes, lacking seamless transitions and consistent virtual identities across different Metaverses [43].

Table 1 juxtaposes the characteristics of traditional networks with those of the new Metaverses, namely the Commercial Metaverse for the general public and the Industrial Metaverse for Industry 5.0 companies. While the Industrial Metaverse shares certain aspects with traditional industrial networks, such as required reliability and latency, it differs significantly in content type and the ability of Meta-Operators to work remotely [44]. This distinction highlights the evolution and potential of the Industrial Metaverse in reshaping industrial landscapes [45]. Advocates of the Metaverse concept envision a forthcoming 3D augmentation of reality, wherein individuals seamlessly engage in commerce, gaming, and collaborative virtual environments. Despite substantial corporate investments, such as Facebook's multi-billion-dollar commitment in recent years, the realization of a 'true' Metaverse remains elusive, with numerous companies laying the groundwork for its eventual emergence [46], [47]. Technological advancements have propelled the development of immersive virtual realities, exemplified by Facebook's exploration of Virtual Reality (VR) through advanced eyeglasses and high-fidelity visuals. Additionally, Augmented Reality (AR) and Mixed Reality (MR) smart glasses have surfaced [48], [49], providing users with supplementary information overlaying their physical surroundings, accessible via various devices ranging from smartphones to personal computers or televisions [50]. For instance, contributions from Microsoft Azure cloud and MR headsets further blur the boundaries between virtual, mixed. and augmented reality, accommodating a spectrum of virtual world experiences spanning from immersive 3D environments to text-based augmented scenarios [51], [52].

Delineating among different Extended Reality (XR) technologies is imperative for comprehending the Industrial Metaverse landscape [53]. In this context, Augmented Reality

(AR) situates users within their physical environment, augmenting it with additional information or modifying it by adding or removing certain elements [54]. This umbrella term encompasses various technologies falling under Mediated Reality, including Assisted Reality (aR), which overlays virtual content to provide additional information [55], and Amplified Reality (amR), which synchronizes the state of additional information publicly among users within the same Industrial Metaverse [56]. Modulated Reality (modR) and Modified Reality (MfR) alter the Meta-Operator's perception by filtering and modifying real elements, while Diminished Reality (DR) and Severely Diminished Reality (SDR) respectively hide or remove real elements or even certain senses from the Meta-Operator's perception, facilitating focused task performance amidst distracting industrial environments [57], [58].

TABLE I
CATEGORIES AND FUNCTIONS OF EXTENDED REALITY (XR) TECHNOLOGIES
IN THE INDUSTRIAL METAVERSE

XR Technologies	Main Points
Behind the	- Augmented Reality (AR) overlays
Metaverse	virtual content onto the physical
	environment.
	- Mixed Reality (MR) smart glasses
	provide supplementary information.
	- Virtual Reality (VR) explores
	immersive virtual realities with high-
	fidelity visuals.
On the Industrial	- Assisted Reality (aR) enhances reality
Metaverse	with additional information.
	- Amplified Reality (amR) synchronizes
	additional information publicly among
	users.
	- Modulated Reality (modR) filters and
	modifies real elements.
	- Modified Reality (MfR) adjusts the
	Meta-Operator's perception digitally.
	- Diminished Reality (DR) hides or
	removes real elements from the
	perception.
	- Severely Diminished Reality (SDR)
	removes entire real environments or
	certain senses.
On Industry 5.0	- XR technologies play a vital role in
	personalized human-machine
	interaction.
	- They facilitate individualized
	interfaces essential for the Industrial
	Metaverse.
	- XR contributes to societal well-being
	by emphasizing human-centric
	trajectories.
	- XR technologies align with the
	European Commission's vision for
	future industrial advancement.

## A. Discussion of Findings

Mixed Reality (MR) combines virtual content with reality, enabling user interaction that produces changes in the physical environment. Objects in the surroundings react to the Meta-Operator's actions, such as virtually damaging machinery upon impact, and maintain a connection to reality [59]. Augmented Virtuality (AV) enriches virtual environments with elements from the real world, allowing Meta-Operators to remain immersed in the virtual world while receiving real-world information [60]. Assisted Virtuality (asV) overlays real-world content on virtual environments to provide accurate information, while Amplified Virtuality (amV) synchronizes provided content among users [61]. Modulated Virtuality (modV) and Modified Virtuality (MfV) alter user perception within virtual environments, easing Meta-Operator tasks or tailoring information based on roles or experience levels [62]. Diminished Virtuality (DV) removes certain virtual elements from the Meta-Operator's perception, akin to restricting access or content in Industrial Metaverses. Virtual Reality immerses Meta-Operators entirely into artificial worlds, which is beneficial for realistic simulations and skill training in industrial scenarios [63], [64].



Fig. 3 Industrial Metaverse AR/MR Tracking Technology

IoT/IIoT data collection is considered for AR and MR technologies for security reasons in Industrial Metaverses, where Meta-Operators interact with machinery. Nonetheless, interaction with IoT/IIoT devices is feasible within virtual worlds and beneficial for AV applications related to digital twins. Figure 4 delineates physical and virtual Industrial Metaverse applications, distinguishing between AR/MR-based interactions with real-world IoT/IIoT objects and those occurring solely in virtual environments. [65], [66].

#### B. Interaction Capabilities of AR/MR

Furthermore, the interaction capabilities of AR/MR devices with the environment vary based on technologies, including marker and markerless approaches. Marker technologies utilize fiducial markers or images to trigger information display or detect objects, while markerless technologies rely on mechanisms like RF beacons, GPS coordinates, motion tracking, and surface detection for environmental understanding [67]-[69].

TABLEII

COMPARES VARIOUS EXTENDED REALITY (XR) TECHNOLOGIES IN TERMS OF THEIR DESCRIPTIONS AND APPLICATIONS IN THE INDUSTRIAL METAVERSE.

XR Technology	Description	Application in Industrial Metaverse
Mixed Reality (MR)	Combines virtual content with reality, enabling user interaction and changes in the physical environment.	Allows Meta-Operators to interact with virtual objects affecting real- world machinery.
Augmented Virtuality (AV)	Enriches virtual environments with elements from the real world while keeping users immersed in the virtual world.	Facilitates Meta- Operators to receive real-world information while engaged in virtual tasks.

XR	Description	Application in
Technology	Description	Industrial Metaverse
Assisted	Overlays real-world	Provides Meta-
Virtuality	content on virtual	Operators with
(asV)	environments to	additional and precise
· /	provide accurate	information overlaid
	information.	onto virtual scenarios.
Amplified	Synchronizes provided	Enhances collaborative
Virtuality	content among users	experiences by ensuring
(amV)	within the virtual	all users view the same
	environment.	additional information
		simultaneously.
Modulated	Alters user perception	Adjusts the presentation
Virtuality	within virtual	of virtual content to suit
(modV)	environments, easing	individual Meta-
	tasks or tailoring	Operators' needs or skill
	information based on	levels.
	roles or experience	
	levels.	
Diminished	Removes certain	Restricts access to or
Virtuality	virtual elements from	removes unnecessary
(DV)	the Meta-Operator's	virtual objects for
	perception.	improved focus or
		security in Industrial
		Metaverses.
Virtual	Immerses users	Facilitates immersive
Reality (VR)	entirely into artificial	training experiences for
	worlds for realistic	Meta-Operators in
	simulations and skill	industrial scenarios.

Edge Computing presents a paradigm shift by offering a decentralized alternative to traditional cloud-based architectures, aiming to address various challenges impacting User Experience (UX), efficiency, accessibility, and privacy. Unlike relying solely on remote clouds, Edge Computing utilizes devices at the network's periphery to perform computing tasks, resulting in faster response times and reduced dependency on cloud resources [70]-[72]. This approach has been applied in Metaverse environments, where

low latency and real-time interactions are crucial for immersive experiences [73]. For instance, solutions like PolyVerse leverage locally deployed Edge Computing devices to project large virtual objects with minimal latency, significantly enhancing user experiences compared to cloudbased alternatives [74].

Moreover, Opportunistic Edge Computing (OEC) systems capitalize on Edge Computing devices to provide services to surrounding IoT/IIoT devices, particularly beneficial in scenarios with intermittent or limited internet connectivity [75]. OEC addresses challenges posed by resourceconstrained IoT/IIoT devices dispersed across vast environments, such as factories, where traditional cloudbased solutions may encounter scalability and accessibility issues [76]. Recent advancements in Single-Board Devices (SBCs), wearables, and embedded IoT/IIoT devices have made OEC feasible and cost-effective, enabling them to act as gateways or smart end devices in Edge Computing architectures for Industrial Metaverse applications [77]. OEC communications exhibit similarities to Mobile Ad-Hoc Networks (MANETs), although OEC offers additional Edge Computing services beyond routing functionalities [78].

While similar paradigms like Proximal Mobile Edge Server, Mobile IoT, and Opportunistic Fog Computing have been proposed in the literature, OEC distinguishes itself by its emphasis on Edge Computing services and its applicability to various IoT/IIoT applications without relying heavily on remote clouds. As illustrated in Figure 6, an OEC architecture for an Industrial Metaverse Factory, dubbed 'Meta-Factory,' showcases the deployment of IIoT devices throughout the factory premises [79]. Meta-operators and autonomous vehicles facilitate monitoring, interaction, and service provision to IIoT devices, even in areas with limited or no communication infrastructure [80]. Meta-operators leverage OEC services to interact with deployed IIoT devices through Industrial Metaverse applications and, when necessary, facilitate communication with remote clouds for tasks requiring intensive computing [81]. This approach ensures efficient data collection, storage, and communication for IIoT devices, enhancing the overall connectivity and functionality of the Industrial Metaverse environment.

TABLE III Software components and their descriptions in the industrial Metaverse

Software Component	Description
Peer	Meta-operators need to detect surrounding IoT/IIoT
Discovery	devices and establish communication channels. To accommodate their mobility and narrow
	communication windows, a secure and fast device
	discovery protocol is required.
Peer Routing	Facilitates routing communications to and from
	specific devices, necessitating the establishment of
	efficient communication paths beforehand.
Data Routing	This enables the OEC system to transmit information
	from one device to another when the receiving device
	is outside the communication range of the sending device.
Resource	Optimizes resource utilization efficiency by
Sharing	delivering necessary resources close to IoT/IIoT and
0	XR devices. This reduces response latency, which is
	critical for enhancing User Experience (UX) in
	Industrial Metaverses.

TABLE IV Standardization initiatives and their descriptions in the Metaverse

Standardization Initiative	Description
ITU	The ITU's Focus Group on Metaverse (FG-MV) involves approximately 500 experts working on potential future standards. It has already delivered over 20 technical specifications and reports. These documents define the metaverse concept, analyze cross-platform interoperability requirements, and detail potential cyber threats.
3GPP	Known for its role in standardizing mobile telecommunications, the 3GPP is currently involved in projects related to the Metaverse, including studies on supporting tactile and multi- modality communication services, providing localized mobile Metaverse services, and delivering XR services.
Metaverse Standards Forum	Established to foster interoperability standards for an open Metaverse without requiring an intellectual property framework, this forum has various operating groups focusing on topics like 3D web interoperability, data asset management, interoperable characters/avatars, network requirements and capabilities, and Industrial Metaverse interoperability.
MPAI	When performing metaverse-related activities, the most significant output is the definition of the MPAI metaverse model.
MPEG	MPEG has added the MPEG Immersive Video (MIV) standard to the MPEG-I suite, which is designed to support XR applications with 6DoF visual interaction.
IEEE	The IEEE proved to be a standard committee with two working groups focusing on AR for mobile devices and creating a methodology for developing Metaverses that considers relevant ethical and social aspects. Initiatives such as the Decentralized Metaverse Initiative and the Persistent Computing for Metaverse Initiative are dedicated to guiding the development of decentralized Metaverses and necessary technologies, respectively.

#### IV. CONCLUSION

This article laid the groundwork for the Meta-Operator concept and offered valuable guidelines for future Industry 5.0 developers. It thoroughly details the key components necessary for creating future Meta-Operators, including essential XR devices and accessories, the development of opportunistic communication protocols, and integration with surrounding IoT/IIoT devices. Additionally, the paper explored the critical aspects of the Industrial Metaverse, recent standardization initiatives, and various options for deploying advanced architectures to enable immersive collaborative experiences. Furthermore, it provided an indepth analysis of the primary development, efficiency, and legal challenges that future Industrial Metaverse developers will face. This paper presented a comprehensive overview of three interconnected concepts-Industrial Metaverse, Meta-Operators, and Industry 5.0-that will collectively drive the next generation of industrial innovation.

#### References

- M. Chyad et al., "Exploring adversarial deep learning for fusion in multi-color channel skin detection applications," Information Fusion, vol. 114, p. 102632, Feb. 2025, doi: 10.1016/j.inffus.2024.102632.
- [2] G. A. Alshafeey, M. M. Lakulu, M. A. Chyad, A. Abdullah, and G. Salem, "Augmented Reality for the Disabled: Review Articles,"

Journal of ICT In Education, vol. 6, pp. 46-57, Jun. 2019, doi:10.37134/jictie.vol6.5.2019.

- [3] K. A. Hossain, "Analysis of present and future use of artificial intelligence (AI) in line of fourth industrial revolution (4IR)", Sci. Res. J., vol. 11, no. 8, pp. 1-50, Aug. 2023.
- [4] A. H. Alamoodi et al., "Machine learning-based imputation soft computing approach for large missing scale and non-reference data imputation," Chaos, Solitons & Fractals, vol. 151, p. 111236, Oct. 2021, doi: 10.1016/j.chaos.2021.111236.
- [5] M. A. Chyad, H. A. Alsattar, B. B. Zaidan, A. A. Zaidan, and G. A. Al Shafeey, "The Landscape of Research on Skin Detectors: Coherent Taxonomy, Open Challenges, Motivations, Recommendations and Statistical Analysis, Future Directions," IEEE Access, vol. 7, pp. 106536–106575, 2019, doi: 10.1109/access.2019.2924989.
- [6] O. S. Albahri et al., "Helping doctors hasten COVID-19 treatment: Towards a rescue framework for the transfusion of best convalescent plasma to the most critical patients based on biological requirements via ml and novel MCDM methods," Computer Methods and Programs in Biomedicine, vol. 196, p. 105617, Nov. 2020, doi:10.1016/j.cmpb.2020.105617.
- [7] K. O. Lewis, V. Popov, and S. S. Fatima, "From static web to metaverse: reinventing medical education in the post-pandemic era," Annals of Medicine, vol. 56, no. 1, Jan. 2024, doi:10.1080/07853890.2024.2305694.
- [8] O. S. Albahri et al., "Fault-Tolerant mHealth Framework in the Context of IoT-Based Real-Time Wearable Health Data Sensors," IEEE Access, vol. 7, pp. 50052–50080, 2019, doi:10.1109/access.2019.2910411.
- [9] A. Giampieri, J. Ling-Chin, Z. Ma, A. Smallbone, and A. P. Roskilly, "A review of the current automotive manufacturing practice from an energy perspective," Applied Energy, vol. 261, p. 114074, Mar. 2020, doi: 10.1016/j.apenergy.2019.114074.
- [10] C. Llopis-Albert, F. Rubio, and F. Valero, "Impact of digital transformation on the automotive industry," Technological Forecasting and Social Change, vol. 162, p. 120343, Jan. 2021, doi:10.1016/j.techfore.2020.120343.
- [11] M. C. Zizic, M. Mladineo, N. Gjeldum, and L. Celent, "From Industry 4.0 towards Industry 5.0: A Review and Analysis of Paradigm Shift for the People, Organization and Technology," Energies, vol. 15, no. 14, p. 5221, Jul. 2022, doi: 10.3390/en15145221.
- [12] E. Rauch, C. Linder, and P. Dallasega, "Anthropocentric perspective of production before and within Industry 4.0," Computers & Industrial Engineering, vol. 139, p. 105644, Jan. 2020, doi:10.1016/j.cie.2019.01.018.
- [13] P. Wang et al., "AR/MR Remote Collaboration on Physical Tasks: A Review," Robotics and Computer-Integrated Manufacturing, vol. 72, p. 102071, Dec. 2021, doi: 10.1016/j.rcim.2020.102071.
- J. Leng et al., "Towards resilience in Industry 5.0: A decentralized autonomous manufacturing paradigm," Journal of Manufacturing Systems, vol. 71, pp. 95–114, Dec. 2023, doi:10.1016/j.jmsy.2023.08.023.
- [15] M. Irpan and S. Shaddiq, "Industry 4.0 and Industry 5.0—Inception, Conception, Perception, and Rethinking Loyalty Employment," *International Journal of Economics, Management, Business, and Social Science (IJEMBIS)*, vol. 4, no. 1, pp. 95-114, 2024.
- [16] R. Tallat et al., "Navigating Industry 5.0: A Survey of Key Enabling Technologies, Trends, Challenges, and Opportunities," IEEE Communications Surveys & Computer Structures, vol. 26, no. 2, pp. 1080– 1126, 2024, doi: 10.1109/comst.2023.3329472.
- [17] D. B. Rawat and D. H. Hagos, "Metaverse Survey & Tutorial: Exploring Key Requirements, Technologies, Standards, Applications, Challenges, and Perspectives," arXiv preprint arXiv:2405.04718, 2024. doi: 10.48550/arXiv.2405.04718.
- [18] N. J. Khalaf, S. Ben Amor, B. Louhichi, J. S. Chiad, and A. Seibi, "Experimental Investigation to Optimize the Manufacturing Parameters of Ankle–Foot Orthoses Using Composite and Titanium Nanoparticles," Journal of Composites Science, vol. 8, no. 2, p. 45, Jan. 2024, doi: 10.3390/jcs8020045.
- [19] Y. P. Tsang, T. Yang, Z. S. Chen, C. H. Wu, and K. H. Tan, "How is extended reality bridging human and cyber-physical systems in the IoT-empowered logistics and supply chain management?," Internet of Things, vol. 20, p. 100623, Nov. 2022, doi: 10.1016/j.iot.2022.100623.
- [20] R. F. Ghazi, J. S. Chiad, and F. M. Abdulghani, "Design and manufacturing a smart shoe for diabetic foot ulcer monitoring and prediction system using internet-of-things technology," Journal of the Brazilian Society of Mechanical Sciences and Engineering, vol. 46, no. 2, Jan. 2024, doi: 10.1007/s40430-023-04591-2.

- [21] E. G. Carayannis, R. Canestrino, and P. Magliocca, "From the Dark Side of Industry 4.0 to Society 5.0: Looking 'Beyond the Box' to Developing Human-Centric Innovation Ecosystems," IEEE Transactions on Engineering Management, vol. 71, pp. 6695–6711, 2024, doi: 10.1109/tem.2023.3239552.
- [22] T. Sharifi, Y. Ghayeb, T. Mohammadi, M. M. Momeni, R. Bagheri, and Z. Song, "Surface treatment of titanium by in-situ anodizination and NiO photodeposition: enhancement of photoelectrochemical properties for water splitting and photocathodic protection of stainless steel," Applied Physics A, vol. 127, no. 1, Jan. 2021, doi:10.1007/s00339-020-03901-y.
- [23] J. Basulo-Ribeiro and L. Teixeira, "The Future of Healthcare with Industry 5.0: Preliminary Interview-Based Qualitative Analysis," Future Internet, vol. 16, no. 3, p. 68, Feb. 2024, doi:10.3390/fi16030068.
- [24] M. Govindaraj, C. Gnanasekaran, R. Kandavel, P. Khan, and S. D. Hoang, "Revolutionizing Service Productivity," Innovative Technologies for Increasing Service Productivity, pp. 41–60, Mar. 2024, doi: 10.4018/979-8-3693-2019-8.ch003.
- [25] M. M. Abdulmunaam and O. S. Farhan, "Finite Element Analysis of Reinforced Self Consolidation Concrete Beams Having a Horizontal Construction Joint," Al-Nahrain Journal for Engineering Sciences, vol. 27, no. 2, pp. 141–148, Aug. 2024, doi: 10.29194/njes.27020141.
- [26] S. Grabowska, S. Saniuk, and B. Gajdzik, "Industry 5.0: improving humanization and sustainability of Industry 4.0," Scientometrics, vol. 127, no. 6, pp. 3117–3144, Apr. 2022, doi: 10.1007/s11192-022-04370-1.
- [27] R. Thapa, S. Poudel, K. Krukiewicz, and A. Kunwar, "A topical review on AI-interlinked biodomain sensors for multi-purpose applications," Measurement, vol. 227, p. 114123, Mar. 2024, doi:10.1016/j.measurement.2024.114123.
- [28] J. M. Górriz et al., "Artificial intelligence within the interplay between natural and artificial computation: Advances in data science, trends and applications," Neurocomputing, vol. 410, pp. 237–270, Oct. 2020, doi: 10.1016/j.neucom.2020.05.078.
- [29] N. A. Sadek, Z. T. Al-Dahan, and S. A. Rattan, "Comprehensive Survey of the State-of-the-Art Deep Learning Models for Diabetic Retinopathy Detection and Grading Using Retinal Fundus Photography," Al-Nahrain Journal for Engineering Sciences, vol. 27, no. 2, pp. 155–163, Jun. 2024, doi: 10.29194/njes.27020155.
- [30] N. Baer and A. Oever, Technics. Amsterdam University Press, 2024. doi: 10.5117/9789048564552.
- [31] L. Montag, "Circular Economy and Supply Chains: Definitions, Conceptualizations, and Research Agenda of the Circular Supply Chain Framework," Circular Economy and Sustainability, vol. 3, no. 1, pp. 35–75, May 2022, doi: 10.1007/s43615-022-00172-y.
- [32] G. da M. Passos Neto, L. H. Alencar, and R. Valdes-Vasquez, "Multiple-Criteria Methods for Assessing Social Sustainability in the Built Environment: A Systematic Review," Sustainability, vol. 15, no. 23, p. 16231, Nov. 2023, doi: 10.3390/su152316231.
- [33] S. E. Bibri, "The Metaverse as a Virtual Model of Platform Urbanism: Its Converging AIoT, XReality, Neurotech, and Nanobiotech and Their Applications, Challenges, and Risks," Smart Cities, vol. 6, no. 3, pp. 1345–1384, May 2023, doi: 10.3390/smartcities6030065.
- [34] Y. K. Dwivedi et al., "Metaverse beyond the hype: Multidisciplinary perspectives on emerging challenges, opportunities, and agenda for research, practice and policy," International Journal of Information Management, vol. 66, p. 102542, Oct. 2022, doi:10.1016/j.ijinfomgt.2022.102542.
- [35] A. I. S. Kubba and A. A. Alammar, "Manufacturing and Testing Pneumatic Pads Adjustable Socket for A Below-Knee Prosthetic," Al-Nahrain Journal for Engineering Sciences, vol. 27, no. 2, pp. 164–168, Aug. 2024, doi: 10.29194/njes.27020164.
- [36] S. K. Jagatheesaperumal and M. Rahouti, "Building Digital Twins of Cyber Physical Systems With Metaverse for Industry 5.0 and Beyond," IT Professional, vol. 24, no. 6, pp. 34–40, Nov. 2022, doi:10.1109/mitp.2022.3225064.
- [37] X. Yao, N. Ma, J. Zhang, K. Wang, E. Yang, and M. Faccio, "Enhancing wisdom manufacturing as industrial metaverse for industry and society 5.0," Journal of Intelligent Manufacturing, vol. 35, no. 1, pp. 235–255, Nov. 2022, doi: 10.1007/s10845-022-02027-7.
- [38] P. A. Rauschnabel, R. Felix, C. Hinsch, H. Shahab, and F. Alt, "What is XR? Towards a Framework for Augmented and Virtual Reality," Computers in Human Behavior, vol. 133, p. 107289, Aug. 2022, doi:10.1016/j.chb.2022.107289.
- [39] M. Tukur et al., "The Metaverse digital environments: A scoping review of the techniques, technologies, and applications," Journal of

King Saud University - Computer and Information Sciences, vol. 36, no. 2, p. 101967, Feb. 2024, doi: 10.1016/j.jksuci.2024.101967.

- [40] P. A. Rauschnabel, B. J. Babin, M. C. tom Dieck, N. Krey, and T. Jung, "What is augmented reality marketing? Its definition, complexity, and future," Journal of Business Research, vol. 142, pp. 1140–1150, Mar. 2022, doi: 10.1016/j.jbusres.2021.12.084.
- [41] Y. Ren, Z. Lv, N. N. Xiong, and J. Wang, "HCNCT: A Cross-chain Interaction Scheme for the Blockchain-based Metaverse," ACM Transactions on Multimedia Computing, Communications, and Applications, vol. 20, no. 7, pp. 1–23, Mar. 2024, doi:10.1145/3594542.
- [42] H. Xie, J. Xu, and Y.-F. Liu, "Max-Min Fairness in IRS-Aided Multi-Cell MISO Systems With Joint Transmit and Reflective Beamforming," IEEE Transactions on Wireless Communications, vol. 20, no. 2, pp. 1379–1393, Feb. 2021, doi: 10.1109/twc.2020.3033332.
- [43] Z. Ma, Y. Wu, M. Xiao, G. Liu, and Z. Zhang, "Interference Suppression for Railway Wireless Communication Systems: A Reconfigurable Intelligent Surface Approach," IEEE Transactions on Vehicular Technology, vol. 70, no. 11, pp. 11593–11603, Nov. 2021, doi: 10.1109/tvt.2021.3111646.
- [44] J. J. K. Chai, C. O'Sullivan, A. A. Gowen, B. Rooney, and J.-L. Xu, "Augmented/mixed reality technologies for food: A review," Trends in Food Science & amp; Technology, vol. 124, pp. 182–194, Jun. 2022, doi: 10.1016/j.tifs.2022.04.021.
- [45] N. Yuviler-Gavish, E. Horesh, E. Shamilov, H. Krisher, and L. Admoni, "The effect of augmented virtuality on financial decisionmaking among adults and children," Virtual Reality, vol. 26, no. 3, pp. 1001–1008, Jan. 2022, doi: 10.1007/s10055-021-00610-6.
- [46] R. Johnstone, N. McDonnell, and J. R. Williamson, "When Virtuality Surpasses Reality: Possible Futures of Ubiquitous XR," CHI Conference on Human Factors in Computing Systems Extended Abstracts, pp. 1–8, Apr. 2022, doi: 10.1145/3491101.3516396.
- [47] K. Anitha, I. Ghosal, and A. Khunteta, "Digital Twins AR and VR," Emerging Technologies in Digital Manufacturing and Smart Factories, pp. 193–204, Feb. 2024, doi: 10.4018/979-8-3693-0920-9.ch011.
- [48] L. Bojic, "Metaverse through the prism of power and addiction: what will happen when the virtual world becomes more attractive than reality?," European Journal of Futures Research, vol. 10, no. 1, Oct. 2022, doi: 10.1186/s40309-022-00208-4.
- [49] R. L. Hornsey and P. B. Hibbard, "Current Perceptions of Virtual Reality Technology," Applied Sciences, vol. 14, no. 10, p. 4222, May 2024, doi: 10.3390/app14104222.
- [50] G.-D. Voinea, F. Gîrbacia, M. Duguleană, R. G. Boboc, and C. Gheorghe, "Mapping the Emergent Trends in Industrial Augmented Reality," Electronics, vol. 12, no. 7, p. 1719, Apr. 2023, doi:10.3390/electronics12071719.
- [51] C. Cacciuttolo, V. Guzmán, P. Catriñir, and E. Atencio, "Sensor Technologies for Safety Monitoring in Mine Tailings Storage Facilities: Solutions in the Industry 4.0 Era," Minerals, vol. 14, no. 5, p. 446, Apr. 2024, doi: 10.3390/min14050446.
- [52] A. Brunzini, M. Ciccarelli, M. Sartini, A. Papetti, and M. Germani, "A comparative study for the assessment of marker-less mixed reality applications for the operator training," International Journal of Computer Integrated Manufacturing, pp. 1–23, Feb. 2024, doi:10.1080/0951192x.2024.2314793.
- [53] A. Assila, A. Dhouib, Z. Monla, and M. Zghal, "Integration of Augmented, Virtual and Mixed Reality with Building Information Modeling: A Systematic Review," Virtual, Augmented and Mixed Reality: Design and Development, pp. 3–19, 2022, doi: 10.1007/978-3-031-05939-1 1.
- [54] R. Ali, R. Liu, Y. He, A. Nayyar, and B. Qureshi, "Systematic Review of Dynamic Multi-Object Identification and Localization: Techniques and Technologies," IEEE Access, vol. 9, pp. 122924–122950, 2021, doi: 10.1109/access.2021.3108775.
- [55] M. Hartmann, U. S. Hashmi, and A. Imran, "Edge computing in smart health care systems: Review, challenges, and research directions," Transactions on Emerging Telecommunications Technologies, vol. 33, no. 3, Aug. 2019, doi: 10.1002/ett.3710.
- [56] K. Rajkumar and U. Hariharan, "Moving to the cloud, fog, and edge computing paradigms: Convergences and future research direction," Artificial Intelligence and Machine Learning for EDGE Computing, pp. 425–442, 2022, doi: 10.1016/b978-0-12-824054-0.00018-6.
- [57] H. Wang et al., "Architectural Design Alternatives Based on Cloud/Edge/Fog Computing for Connected Vehicles," IEEE Communications Surveys & Tutorials, vol. 22, no. 4, pp. 2349–2377, 2020, doi: 10.1109/comst.2020.3020854.

- [58] A. Hazarika and M. Rahmati, "Towards an Evolved Immersive Experience: Exploring 5G- and Beyond-Enabled Ultra-Low-Latency Communications for Augmented and Virtual Reality," Sensors, vol. 23, no. 7, p. 3682, Apr. 2023, doi: 10.3390/s23073682.
- [59] Y. Cao, J. Cao, D. Bai, Z. Hu, K. Wang, and M. Zhang, "PolyVerse: An Edge Computing-Empowered Metaverse with Physical-to-Virtual Projection," 2023 International Conference on Intelligent Metaverse Technologies & amp; Applications (iMETA), pp. 1–8, Sep. 2023, doi:10.1109/imeta59369.2023.10294558.
- [60] M. B. Shahab, R. Abbas, M. Shirvanimoghaddam, and S. J. Johnson, "Grant-Free Non-Orthogonal Multiple Access for IoT: A Survey," IEEE Communications Surveys & amp; Tutorials, vol. 22, no. 3, pp. 1805–1838, 2020, doi: 10.1109/comst.2020.2996032.
- [61] G. Nain, K. K. Pattanaik, and G. K. Sharma, "Towards edge computing in intelligent manufacturing: Past, present and future," Journal of Manufacturing Systems, vol. 62, pp. 588–611, Jan. 2022, doi:10.1016/j.jmsy.2022.01.010.
- [62] P. M. Sánchez Sánchez, J. M. Jorquera Valero, A. Huertas Celdrán, G. Bovet, M. Gil Pérez, and G. M. Pérez, "A methodology to identify identical single-board computers based on hardware behavior fingerprinting," Journal of Network and Computer Applications, vol. 212, p. 103579, Mar. 2023, doi: 10.1016/j.jnca.2022.103579.
- [63] H. K. Sharaf, S. Alyousif, N. J. Khalaf, A. F. Hussein, and M. K. Abbas, "Development of bracket for cross arm structure in transmission tower: Experimental and numerical analysis," New Materials, Compounds and Applications, vol. 6, no. 3, pp. 257–275, 2022.
- [64] C. Mao and D. Chang, "Review of cross-device interaction for facilitating digital transformation in smart home context: A usercentric perspective," Advanced Engineering Informatics, vol. 57, p. 102087, Aug. 2023, doi: 10.1016/j.aei.2023.102087.
- [65] A. H. T. Al-Temimi, Y. J. Lafta, I. O. Bachi Al-Fahad, and H. K. Sharaf, "Study the Influence of Impact on the Filled Tube of Aluminum 6082-T6 Alloy by Consideration of Temperature using FEM," Journal of Advanced Research in Fluid Mechanics and Thermal Sciences, vol. 122, no. 2, pp. 118–129, Oct. 2024, doi:10.37934/arfmts.122.2.118129.
- [66] S. A. Nawi, H. B. Mohammed, A. N. Jasim, H. K. Sharaf, and M. T. Muhammad, "Numerical Analysis of the Influence of the Rolling Speed on the Cold Rolling under Specific Thermal Condition of the AA 5052-O Aluminum Alloy," Journal of Advanced Research in Fluid Mechanics and Thermal Sciences, vol. 122, no. 1, pp. 69–79, Oct. 2024, doi: 10.37934/arfmts.122.1.6979.
- [67] I. O. Bachi Al-Fahad and Hussein Kadhim Sharaf, "Investigation of the Effect of Heat Transfer during Friction Stir Welding (FSW) of AZ80A Mg Alloy Plates using a Pin Tool by Conducting Finite Elements Analysis," Journal of Advanced Research in Fluid Mechanics and Thermal Sciences, vol. 117, no. 1, pp. 98–108, May 2024, doi: 10.37934/arfmts.117.1.98108.
- [68] B. A. Sadkhan, S. H. Omran, and H. K. Sharaf, "An Experimental Analysis on the Impact of the Epoxy on the Torsional Behavior of Composite Fiber-Glass," Journal of Advanced Research in Applied Mechanics, vol. 117, no. 1, pp. 150–160, Jun. 2024, doi:10.37934/aram.117.1.150160.
- [69] A. Fattahi, H. K. Sharaf, and N. Mariah, "Thermal Comfort Assessment of UPM Engineering Library in Tropical Climate Conditions," Journal of Advanced Research in Applied Mechanics, vol. 117, no. 1, pp. 179–189, Jun. 2024, doi:10.37934/aram.117.1.179189.
- [70] B. A. Sadkhan, E. J. Yousif, A. T. Shomran, E. K. Hussein, and H. K. Sharaf, "Investigation of the Impact Response of Plain Weave E-Glass Composite Structure Based on the EN ISO 178 Standard," Journal of Advanced Research in Applied Mechanics, vol. 117, no. 1, pp. 118–127, Jun. 2024, doi: 10.37934/aram.117.1.118127.
- [71] Y. M. Abdullah, G. S. Aziz, H. K. Salah, and H. K. Sharaf, "Simulate the Rheological Behaviour of the Solar Collector by Using Computational Fluid Dynamic Approach," CFD Letters, vol. 15, no. 9, pp. 175–182, Aug. 2023, doi: 10.37934/cfdl.15.9.175182.
- [72] A. H. A. Bari, R. A. Abed, R. M. Kahdim, H. F. Hasan, H. K. Sharaf, and A. S. Alwan, "The role of internal auditing in corruption control and enhancing corporate governance: A board of directors' outlook," Corporate Board: Role, Duties and Composition, vol. 20, no. 2, pp. 120–127, 2024, doi: 10.22495/cbv20i2art12.
- [73] F. T. Al-Maliky and J. S. Chiad, "Study and analysis the flexion moment in active and passive knee prosthesis using back propagation neural network predictive," Journal of the Brazilian Society of

Mechanical Sciences and Engineering, vol. 44, no. 11, Oct. 2022, doi:10.1007/s40430-022-03850-y.

- [74] H. A. Saleh, A. R. Ali, A. N. S. Almshabbak, H. K. Sharaf, H. F. Hasan, and A. S. Alwan, "The impact of auditor-client range on audit quality and timely auditor report," Corporate and Business Strategy Review, vol. 5, no. 1, special Issue, pp. 329–335, 2024, doi:10.22495/cbsrv5i1siart7.
- [75] I. O. B. Al-Fahad, A. D. Hassan, B. M. Faisal, and H. kadhim Sharaf, "Identification of regularities in the behavior of a glass fiberreinforced polyester composite of the impact test based on ASTM D256 standard," Eastern-European Journal of Enterprise Technologies, vol. 4, no. 7 (124), pp. 63–71, Aug. 2023, doi:10.15587/1729-4061.2023.286541.
- [76] I. O. B. Al-Fahad, H. kadhim Sharaf, L. N. Bachache, and N. K. Bachache, "Identifying the mechanism of the fatigue behavior of the composite shaft subjected to variable load," Eastern-European Journal of Enterprise Technologies, vol. 3, no. 7 (123), pp. 37–44, Jun. 2023, doi: 10.15587/1729-4061.2023.283078.
- [77] K. A. Subhi, E. K. Hussein, S. A. K. Al-Jumaili, and Z. A. Abbas, "Implementation of the numerical analysis of dynamic loads on the composite structure employing the FE method," Eastern-European

Journal of Enterprise Technologies, vol. 1, no. 7(115), pp. 42–47, Feb. 2022, doi: 10.15587/1729-4061.2022.253545.

- [78] L. T. Mouhmmd, M. A. Rahima, A. M. Mohammed, H. F. Hasan, A. S. Alwan, and H. K. Sharaf, "The effect of firm type on the relationship between accounting quality and trade credit in listed firms," Corporate and Business Strategy Review, vol. 4, no. 2, pp. 175–183, 2023, doi:10.22495/cbsrv4i2art16.
- [79] M. A. Burhanuddin, A. A.-J. Mohammed, R. Ismail, M. E. Hameed, A. N. Kareem, and H. Basiron, "A Review on Security Challenges and Features in Wireless Sensor Networks: IoT Perspective", JTEC, vol. 10, no. 1-7, pp. 17–21, Feb. 2018.
- [80] C. Zheyuan, A. T. Hammid, A. N. Kareem, M. Jiang, M. N. Mohammed, and N. M. Kumar, "A Rigid Cuckoo Search Algorithm for Solving Short-Term Hydrothermal Scheduling Problem," Sustainability, vol. 13, no. 8, p. 4277, Apr. 2021, doi:10.3390/su13084277.
- [81] F. M. Aswad, A. N. Kareem, A. M. Khudhur, B. A. Khalaf, and S. A. Mostafa, "Tree-based machine learning algorithms in the Internet of Things environment for multivariate flood status prediction," Journal of Intelligent Systems, vol. 31, no. 1, pp. 1–14, Nov. 2021, doi:10.1515/jisys-2021-0179.