Taking Autonomous Mobile Robots and Humans Into the Industrial Metaverse: An Empirical Study in the Automotive Industry

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***Abstract*—This paper provides empirical insights into a new emerging robot-related trend, in which Autonomous Mobile Robots (AMRs) are used for building an industrial metaverse. The aims of this study were to a) develop a technical solution for AMR-enabled metaverse creation, b) to test and demonstrate the solution in a real industrial case, and c) to identify future "factory metaverse" concepts within the automotive industry. This paper presents the new solution combining an AMR-enabled digital shadow (point cloud) creation, transfer of the point cloud to an eXtended Reality (XR) platform, and data visualisation, audio and multi-user interaction in the virtual factory metaverse. The solution was tested and demonstrated in Valmet Automotive's Innovation Center in Finland. Potential future use cases and concepts were identified through a qualitative case study (n=36). The solution enables remote and multi-user situational awareness and collaboration. Potential use cases for the factory metaverse include, e.g., factory cell and work planning, remote technical support, and safety trainings.**

Keywords–Autonomous mobile robot; industrial metaverse; extended reality; virtual reality; digital twin.

I. INTRODUCTION

The concept of the metaverse has been widely discussed especially since 2021, when Facebook changed their company name to Meta. Originally, the metaverse concept was mentioned as early as 1992 by Neal Stephenson in a science fiction novel called Snow Crash [1]. According to the author, the metaverse was regarded as "a three-dimensional virtual space that uses the metaphor of the real world, and where humans, as programmable avatars, interact with each other and software agents". This description still addresses the central elements of the metaverse concept quite effectively.

In the research literature, there is a lack of a comprehensive definition of the metaverse. It is defined, for instance, as "a three-dimensional online environment in which users represented by avatars interact with each other in virtual spaces decoupled from the real physical world" [2]. The metaverse involves a set of technologies such as smart devices, avatars, Artificial Intelligence (AI), Virtual Reality (VR), Augmented Reality (AR), XR, digital twins, blockchains, and robotics [3]-[5].

Recently, the metaverse has captured the attention of both academia and industry practitioners [6]. So far, the focus has predominantly been on consumer applications although the largest business potential is seen in industrial metaverse applications [7][8]. Wider application of the metaverse is still in its earliest stages and especially so in the industrial context. This study aims to provide empirical insights into metaverse applications and potential future concepts focusing specifically on the industrial B2B context. The underlying goal is to make industrial work in the manufacturing sector more efficient, safe, and motivating.

Within the industrial and operations management domain, the industrial metaverse can enable virtual employee training and collaboration, virtual prototyping, and virtual-showroom displays for products [9]. The metaverse may have many implications on product development, manufacturing, and customer relationships [3]. As COVID-19 enhanced teleworking globally, the metaverse can develop remote work and collaboration to a whole new level [10]. Arguably, the metaverse is a growing topic in production and operation research. However, more research is called for [11][12] and there is a lack of empirical studies regarding the ways industrial companies can adopt the metaverse into their operations [13].

VTT Technical Research Centre of Finland, in collaboration with 10 industrial partners, identified robotics-aided metaverse as one of the most promising industrial metaverse applications [14]. AMRs and Automated Guided Vehicles (AGVs) are nowadays commonly used for, e.g., internal logistics tasks [15]. AMRs equipped with laser scanners have the capability to sense their environments and form a 3D model (point cloud) of its surroundings for navigation and safety [15]. A link to the metaverse can thus also be built from autonomous digital shadow creation to a wider metaverse application including extended reality (XR) solutions.

The aim of this paper is to increase understanding of a robotics-assisted industrial metaverse and potential future concepts in the manufacturing sector. More specifically, the aim of this study was to a) develop a technical solution for AMR-enabled metaverse creation, b) to test and demonstrate the solution in a real industrial case, and c) to identify future "factory metaverse" concepts within the automotive industry. The study results present the developed new metaverse solution, its features, and future autonomous factory metaverse concepts. A qualitative case study (n=36) was conducted in Valmet Automotive to innovate and identify potential use cases and future factory metaverse concepts.

The novelty value of this research derives from the creation of a new industrial metaverse application combining AMRs and XR, and the identification of its potential use cases in real-life industrial operations. The study is among the first empirical metaverse studies within the production and operations management domain and it provides a concrete example of the ways the industrial metaverse can be realised in the future.

This paper is organised as follows: Section 1 presents an introduction to the paper. In Section 2, theoretical background and literature synthesis are provided. Section 3 outlines the methodology of the study. Section 4 presents the study results: a) description of the new factory metaverse solution and b) identified new use cases and concepts. In Section 5, study contribution, limitations, and potential future research avenues are discussed.

II. THEORY

This Section outlines the theoretical background concerning industrial metaverse, digital twins, AMRs, and XR solutions. Finally, the Section synthesizes the literature review and research needs.

A. *Industrial metaverse and digital twins*

The industrial metaverse "combines physical-digital fusion and human augmentation for industrial applications and contains digital representations of physical industrial environments, systems, assets and spaces that people can control, communicate, and interact with" [8]. Potential applications in the production and operations management domain include, e.g., simulation and testing of different scenarios at the design stage [3]. The metaverse offers multiple opportunities for production systems, training, and agile virtual prototyping [9]. The metaverse enables people to join the design at any time from any place and communicate to each in a common digital environment. Thus, it enhances the trend of remote work and operations. The metaverse allows companies to simulate and optimise factory planning and complex industrial processes the way, for instance, BMW has done [16].

Metaverse is a technology to support the well-established frameworks and initiatives in the manufacturing sector such as Industry 4.0 and 5.0 [17]. Both streams identify robotics and digital twins as central disruptive technologies. Applications involving digital twins and simulations are central components of the industrial metaverse [18]. Changes taking place in the real world reflect the digital twin, and vice versa. Mirroring and simulating real machines, factories, cities, and other complex systems in the digital world will enable industries to solve complex real-world problems digitally and perform predictive maintenance [19].

Digitisation can be divided into three categories: digital model, digital shadow, and digital twin [20]. The digital model can be done of a physical object (e.g., a CAD model of a machine), but there is to be no automatic data exchange between the physical model and the digital model. A digital shadow is a digital representation of an object that has a one-way flow between the physical and digital object; once the physical entity changes, the digital shadow changes respectively. However, digital twins are at the core of metaverse thinking, which is that virtual and physical reality will merge into one (or at least they begin to resemble each other as much as possible). Changes in either one is to be updated automatically in the other one. To obtain a full metaverse, the digital twin must be dynamically updated according to the changes happening in physical reality. [20]

We propose that one potential way to pave the path towards viable industrial metaverse solutions is to use AMRs for autonomous geospatial digital shadow creation and updates. In addition to digital shadow creation, AMRs can collect localised data to be augmented in the digital shadow [21]. Robots, in particular social robots, are mentioned as one of the central metaverse technology enablers [5]. However, there is a lack of empirical metaverse studies, particularly any involving industrial B2B AMRs and studying their linkages to the metaverse phenomenon.

B. *AMRs and XR solutions*

By definition, Autonomous Mobile Robots (AMRs) are "industrial robots that use a decentralised decision-making process for collision-free navigation to provide a platform for material handling, collaborative activities, and full services within a bounded area" [15]. The robots detect their surroundings with multiple sensors (e.g., laser scanners and cameras), move and navigate autonomously and avoid collisions with obstacles or humans [22]. Nowadays, AMRs very commonly contain 3D Light Detection And Ranging (LiDAR) scanners for Simultaneous Location and Mapping (SLAM). By forming a point cloud, i.e., a digital 3D reconstruction of the environment, they are able to autonomously navigate on their reassigned routes or areas, and avoid collisions [22].

LiDAR-based point clouds can be regarded as up-to-date digital shadows of factories. This kind of autonomously created digital shadow has been previously used for enhanced situational awareness and change detection in factories [23]. We regard autonomous digital shadow creation as the first phase needed for industrial metaverse creation. Consequently, we propose the autonomously created digital shadow to be augmented with multimodal data visualisation and multiuser interaction modalities in an immersive factory metaverse. For these purposes, XR solutions offer wide possibilities.

XR solutions are central technological enablers in the metaverse phenomenon [3]-[5]. Research on interconnections between XR and robotics is abundant. Earlier research has addressed the following cases for VR and AR solutions for human–robot interaction: operator support, simulation, instruction, and manipulation [24]. AR and VR solutions can be used, for instance, for robot task planning [25] and mobile robot fleet visualisation [26]. Digital twins and the metaverse can serve as a virtual testing ground for new robot designs [5]. However, empirical insights on autonomous creation of factory metaverses with immersive, multiuser interaction features remain limited.

C. *Literature synthesis*

The industrial metaverse is an emerging research topic within the Production and Operations Management (POMS) literature [12][13]. However, empirical research on concrete industrial metaverse applications remains limited. More empirical insights are needed on the interconnection of AMRs and the ways they could enhance metaverse applications. In particular, more knowledge is needed on the implications of an industrial metaverse on industrial operations.

As the basis for creating a "factory metaverse", a geospatial digital shadow is needed. XR solutions, as such, do not offer a possibility for automatic and up-to-date digital shadow creation. This is something that AMRs can do. AMRs can create up-to-date digital shadows automatically with their LiDARs and cameras [23]. That way, there is always an up-to-date digital shadow available. In addition to the digital shadow creation, AMRs can collect data in the factory.

The role of AMRs has already been noted in the literature concerning central industrial metaverse technologies [27]. However, empirical studies addressing interconnections between AMRs and metaverse, and potential new industrial metaverse concepts and applications, remain scarce. Our study combines AMRs, digital shadows, data visualisation, and multi-user interaction in an immersive XR environment in the automotive industry context. This study provides empirical insights on the ways autonomous metaverse solutions can enhance industrial operations in the future.

III. METHODOLOGY

The main research question of this study is: *"How can a new AMR-assisted metaverse solution support industrial operations in the manufacturing sector?"* In order to increase understanding of a new, underinvestigated phenomenon, and to answer "how" questions, this study applies a qualitative case study approach [28]. This study combined technical development, real-life testing and demonstration, and a qualitative single case study with group interviews taking place after testing and demos. Developing and testing a new robot metaverse solution concretised the emerging phenomenon, gave concrete testing results for further technical development, and facilitated innovation of new concepts with the industrial representatives.

The study was conducted in cooperation between the VTT Technical Research Centre of Finland and Telia Finland Ltd. Telia is a large telecom company situated in the Nordic countries in Europe. Telia's main business relies on mobile networks (e.g., 5G) and telecommunications services. Their interest in this study arose from their industrial services business line and innovation of new potential future robotics and metaverse-related services. The industrial metaverse can be considered a new communication platform, therefore a core service offering for a telecom operator. Widescale deployments will also impact the industrial customers' ICT architectures as more computational capacity will be needed close to the end users and supported with low latency, high bandwidth connectivity.

In this study, VTT was responsible for the technical development work. Solution testing, demonstrations, interviews, data analysis, conclusions and reporting were conducted in cooperation between VTT and Telia. The VTT-Telia collaboration took place as a part of a large research project MURO – "Multi-purpose service robotics as an operator business" (2021-2023). Finalizing the paper and publication took place in VTT's MixedFleet project.

The AMR-enabled metaverse solution developed and studied bases on an autonomous SPOT mobile robot platform (Figure 1), the Trimble X7 LiDAR scanner and Unity game engine.

Figure 1. Autonomous scanning of Valmet Automotive's Innovation Center.

Boston Dynamics' SPOT robot represents a mobile robot with outstanding balance and mobility skills. Compared to wheeled AMRs, SPOT can move on, e.g., stairs, doorsteps, and uneven terrains. Thus, it opens up new application opportunities in many industries. In this project, the main task of the robot was to autonomously create a point cloud – in effect, a 3D geospatial digital shadow – of Valmet Automotive's Innovation Center.

In this project, the Unity platform was used for virtual world creation. Unity is a cross-platform game engine developed by Unity Technologies. It is widely used for video games, but also for professional applications in various industries. In addition to the SPOT robot and Trimble X7 scanner, a 360 camera was used. It enabled video creation in selected Points of Interest (PoIs) in the 3D model. Surrounding audio was recorded with a Zoom H4n audio recorder.

Valmet Automotive's Innovation Center was selected as the testing and demonstration site. Headquartered in Finland, Valmet Automotive is a versatile service provider for the automotive industry, one of the largest vehicle contract manufacturers in the world, and currently makes vehicles for Mercedes-Benz and Mercedes-AMG. There is a welding robot demonstration cell in the Innovation Center. It was scanned both from outside and inside in order to enable people “going inside” the robot cell in the created factory metaverse. In normal situations, naturally people are not allowed to go inside the robot cell while the robots are moving, but in the virtual world or “metaverse” people can do so virtually and remotely.

Technical development focused on building a pipeline from SPOT robot-enabled autonomous scanning to factory metaverse creation and use in VR. Technical development work proceeded in the following steps:

1. Physical and software integration between the SPOT robot platform and the Trimble scanner
2. Activation of autonomous scanning features of the SPOT&Trimble combination
3. Autonomous point cloud capture and data collection in the Valmet Automotive Innovation Center:
    - Autonomous point cloud capture with SPOT robot Autowalk functionality and Trimble X7 scanner
    - 360 video shoots
    - Audio sample recording
4. Unified point cloud creation with a Trimble FieldLink application
    - Individual scan registration to a unified point cloud
    - Addition of colour information
    - Export of the complete point cloud as an E57 file from the FieldLink
5. Point cloud processing
    - Removing of unnecessary areas and downsampling (3 mm minimum point distance) in CloudCompare
6. Development of point cloud to Unity import pipeline using the Pixyz Plugin for Unity
7. Importing the point cloud to Unity including segmentation of the point cloud, generation of Level of Detail (LOD) groups for PoIs, and a collider mesh for interaction
8. Development of the OpenXR-based device agnostic XR application platform in Unity
9. Development of user interfaces supporting XR devices, traditional keyboard and mouse interaction using the Unity XR Interaction Toolkit together with the XR Device Simulator
10. Development of multi-player features with Unity Netcode for GameObjects Software Development Kit (SDK) and Dissonance Voice Chat plugin
11. Adding 360 still images and videos to provide a detailed view of the key PoIs
12. Adding audio data in Unity with location so that the factory audio (e.g., a machine voice) always comes from the right direction for the user.

In addition to technical R&D, a qualitative case study was conducted. The purpose of the case study was to gain deeper understanding regarding the metaverse phenomenon and its potential applications in the practical industrial world. The case study included a literature review, metaverse solution demonstration in Valmet Automotive, data collection with group discussions (n=36) and interviews with a part of the group discussion and demo participants (12 informants), analysing and summarising the interview data, and drawing conclusions. In the discussions and interviews, the informants were asked to describe their initial impressions after testing the solution, and to bring up ideas for potential use cases in factory operations.

Thus, the results of this study are twofold: 1) the developed and tested new AMR-enabled factory metaverse solution and 2) the identified factory metaverse use cases and concepts.

IV. RESULTS

This Section presents the results of the study. It describes the created AMR-enabled factory metaverse solution, its features and the identified potential use cases and concepts in the automotive industry.

A. *AMR-enabled factory metaverse solution*

As the main result of the study, an AMR-enabled factory metaverse solution was created. The SPOT robot operated as the autonomous mobile platform for the developed metaverse-pipeline. Together with a high-speed Trimble X7 laser scanner mounted on the SPOT, autonomous scanning was made possible for generating point clouds. The rest of the development work was done in Unity. Figure 2 illustrates the pipeline from autonomous scanning, through the mesh creation process, to the virtual model:

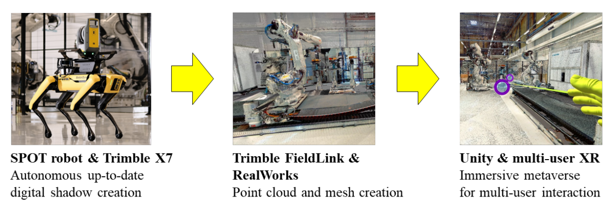

Figure 2. Pipeline from autonomous scanning to immersive, multi-user metaverse creation and utilisation.

The factory metaverse solution includes the following features:

- Immersive 3D view, factory audio and movement in an accurate and up-to-date factory metaverse
- Annotations: the possibility to add, modify and delete annotations, e.g., notes
- Versatile data visualisation and PoIs with still images and video feed
- Multi-user use, hosting and joining of a team session
- Visible avatars (head, hands and name) and interaction with a multiplayer voice chat feature
- Many user interface possibilities: can be used with XR devices, a basic keyboard or a mouse
- As XR device-agnostic as possible

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- Annotation information in a remote database, making the annotations persistent between multiple sessions.

Users can view the factory metaverse with VR glasses or on a desktop. By clicking PoIs, the user sees still images and video feed of the robots operating. Figure 3 presents a 360 camera view and a point cloud, a digital “shadow”, of the robot cell in Valmet Automotive’s Innovation Center.

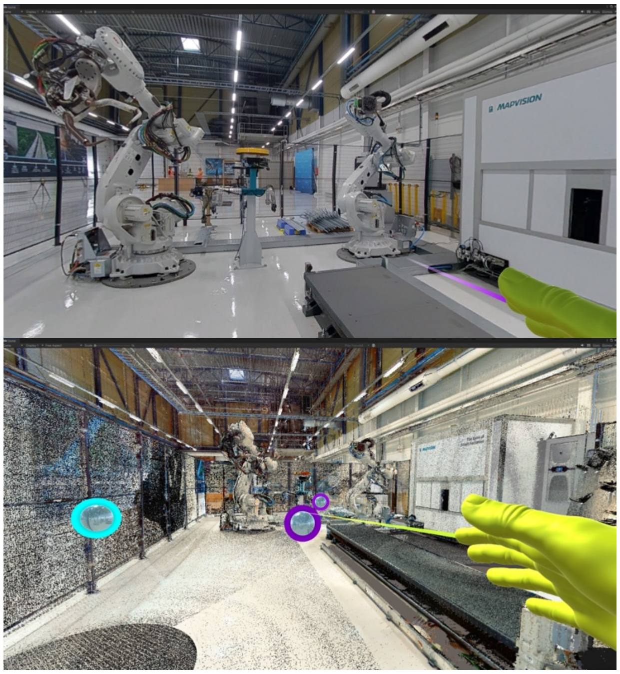

Figure 3. 360 camera view and a point cloud of the robot cell.

B. *Factory metaverse use cases and concepts*

As a result of the qualitative case study, several new AMR-enabled factory metaverse concept ideas were collected from the company representatives. The car manufacturer has a virtual R&D team distributed in several countries. They could use the autonomously created metaverse in their product design. They could represent new production techniques to their business customers in a 3D metaverse. The solution enables users to go virtually “inside” the welding robot cell while the robot is working, which would not be possible in real life for safety reasons. Then, an immersive experience would be achieved for the customers in product and manufacturing technique representations. As a director of the company pointed out regarding the related benefits: *“World-class car manufacturing competence is what we are selling. If we can concretise and visualise our competences in a better way for our clients, a superior customer experience can be offered. We will also be a forerunner in that sense.”*

According to the interviewees, the solution could be used in manufacturing cell layout and process design. A virtual team comprising several organisational units, could combine their competences, plan and visualise optimal ways to conduct assembly work together within an autonomously created virtual world. As car manufacturing is a highly demanding and efficient process, all kinds of pre-planning is extremely important, when any changes are proposed for the manufacturing line. The interviewees saw that the metaverse solution brings benefits for their central need for careful design, testing and planning in everything that takes place in the factory. Also in internal logistics operations, an up-to-date 3D model could be used for material handling processes planning and optimisation.

When a factory metaverse would be created and updated autonomously with mobile robots, the 3D model could also entail information on tidiness and safety issues. The robot could autonomously and automatically detect safety risks and deficiencies and update the data in the factory metaverse. Then, the factory metaverse could also be used in safety and assembly work trainings. As in planning and R&D, trainings could also be conducted remotely and still in a very realistic way. In repair and maintenance, an autonomously created metaverse could be used for remote technical support. As an interviewee described: *“The expert wouldn’t need to fly from the other end of the world, but he/she could provide technical support and advice remotely inside the shared metaverse”* What they also emphasised was the fact that all remote work and decreasing travelling supports the company’s sustainability goals.

The ICT Director of the company brought up the need for an iterative process between the digital model and real world to ensure up-to-date metaverse and data. This need is at the very core of metaverse thinking according to which the real world and metaverse would closely resemble each other and updates to either one would also take place in the other “reality”.

As a summary, the interviewees saw a lot of potential for the new solution and identified several operations the new solution could support. Further development needs they brought up related to the price of autonomous robots, lack of real-time updating of the model, and usability issues and simulator sickness while using VR glasses. Table 1 summarizes the identified new robot metaverse concepts and operations they support in manufacturing.

TABLE I. FACTORY METAVERSE USE CASES AND CONCEPTS

Industrial operation	**Factory metaverse use cases and concepts**
Product design	• Remote R&D team collaboration • Product design and updates visualisation
Manufacturing	• Robot and manufacturing cell design • Assembly work planning and training • New personnel onboarding and training
Internal logistics	• Planning, visualisation and optimisation of material handling
Repair and maintenance	• Machine data collection and visual display • Remote technical support from global experts
Sales and marketing	• Presenting new car designs for the customer • Demonstration and visualisation of world-class manufacturing competences for the customer
Safety	• Safety risk identification and collection autonomously and visual data display • Safety trainings

V. CONCLUSIONS

This Section outlines the study contribution, its limitations and potential future research avenues.

A. Study contribution and discussion

Despite the increasing interest and future business potential related to the industrial metaverse [2]-[6] and the salient role of both XR and AMR technologies as a part of the phenomenon [3][5], empirical research on new industrial metaverse solutions remains limited in the operations management domain. This study created a *pipeline from autonomous SPOT robot-enabled digital shadows to immersive, interactive, multi-user factory metaverse*, and demonstrated the solution in the automotive industry case. The study contributes by presenting the new technological solution and managerial insights into the potential use cases and future factory metaverse concepts.

XR solutions have been widely applied and studied before [3][5]. However, the novelty value of this study is derived from building the metaverse based on AMRs with LiDAR scanners and covering the whole pipeline from autonomous point cloud capture to factory metaverse creation and use. Firstly, autonomous scanning accrues several benefits. AMRs can go around a large factory and factory area and repeteadly scan the environment and collect beneficial data and identify anomalies. No manual, time-consuming scannings are then needed, and even more importantly, the digital shadow of the factory always remains up-to-date with beneficial data. Quite often, a problem with digital geospatial shadows or any sort of factory 3D models is that after they are created once, some changes take place in the factory imminently thereafter and the model becomes obsolete and useless. AMRs' autonomous regular scanning rounds tackle this problem.

Another novelty value and benefit of the solution is the fact that its basis is LiDAR-based point clouds instead of 2D pictures. The metaverse is then accurate in terms of dimensions, 3D view and experience. When something is annotated in the model, it is in the right coordination and location. You can move and interact inside the metaverse and see, e.g., a welding robot in 3D and look around it from all directions and angles. This facilitates solving technical problems together remotely in the metaverse as you can, e.g., point out a certain component specifically for which the solving of a given problem concerns the robot. You can "go inside" a welding robot cell while it is operating, which is naturally not possible in the real world for safety reasons.

The factory metaverse solution was demonstrated and tested in the Valmet Automotive Innovation Center. Company representatives identified the following use cases and concepts as having the most potential in the future: remote R&D team collaboration in product design, planning of manufacturing cells and work tasks, remote technical support work, and new personnel onboarding and safety trainings. The multi-user feature of the factory metaverse solution provides several benefits and future application opportunities by enhancing remote collaboration, ideation, and technical support, as well as knowledge sharing, visualisation and competence building over the organisational silos.

The company representatives found the solution as a promising and illustrating example of future industrial metaverse solutions. However, more clarification is needed, e.g., on the way the new solution complements and offers added value to the existing solutions already in use in the factory. Although further R&D and testing is needed, this study is one of the first empirical industrial metaverse studies with a new technical solution and demonstration complementing earlier metaverse research within the operations management domain [12][13].

B. Limitations and future research avenues

As with all research endeavours, this one had its limitations, which on the other hand also provide potential future research avenues. The first limitation concerns the fact that this was one of first attempts to build a pipeline from the SPOT robot point cloud capture to XR. All parts of the solution were developed and demonstrated successfully. However, there are still plenty of manual work phases and the pipeline does not transition automatically from scanning to a ready factory metaverse. Attempts to automate and make the solution as real-time as possible are potential avenues for future R&D.

Another limitation is that this study only included one case. Multiple case studies would provide more versatile insights both in terms of further R&D needs and potential use cases. Different use environments may hinder the use of AMRs. For instance, using the SPOT robot autonomously in public areas may entail safety risks, so it is one limitation of this specific solution. In addition, reflective surfaces and monotonous, repetitive environments may cause challenges for LiDAR scanning. Consequently, more research should be conducted in order to evaluate the viability and feasibility of the solution in different contexts and use environments.

Manifestation of an autonomous factory metaverse is a research topic that may quite certainly attract more attention and interest both within academia and the business world in the future. An AMR can be equipped with multiple sensors enhancing extensive multimodal data collection and transfer. Sophisticated computer vision adds capabilities for robots enabling identification of, e.g., anomalies and safety risks. Both robots' own status data and data they collect from the factory can be brought into the factory metaverse for enhanced situational awareness and safety. As an industrial metaverse includes many similar aspects to Industry 4.0 and 5.0, more research is needed on the overlaps, differences and linkages between the phenomena. For instance, immersive experience and multi-user collaboration are highlighted in the metaverse phenomenon. Especially from this perspective, more research is needed on the related industrial applications and potential added value for operations management.

As this study concentrated on the autonomous creation of a factory metaverse representing a digital "shadow" of the factory, more research could continue in studying feedback loops from the digital shadow back to the reality based on human and team actions taken in the metaverse. Then, we will get closer to the core idea of the metaverse: the digital and real world merge and become more and more as one.

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