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*i*MetaverseKG: *I*ndustrial Metaverse Knowledge Graph to Promote Interoperability in Design and Engineering Applications

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The term metaverse was coined by author Neal Stephenson in 1992 in his science fiction novel "Snow Crash."[1] Metaverse is a conjunction of the Greek prefix "meta," which means beyond, and the stem "verse," which implies universe, hence the meaning "beyond the universe." It is a futuristic, hyperrealistic virtual world where humans will spend time performing their day-to-day activities, such as entertaining, socializing, playing, working, and shopping. This requires that a metaverse offers a real-time virtual representation of the physical world with its entities, relationships, events, states, processes, and activities. According to the Gartner forecast report, the metaverse is among the top five emerging trends and technologies. Gartner predicts that by 2026 25% of people will spend at least one hour every day in the metaverse and 30% of organizations will have products and services developed for metaverse platforms.[2] The metaverse is in an early developmental stage but has a considerable promise of occupying prominent space in the next phase of the Internet.

Today, Neal Stephenson's vision of a virtual world is becoming a reality across various sectors, with early popularity in gaming,[3] consumer products,[4] and enterprise collaboration.[5] Emerging metaverse platforms can be divided into two main categories: social metaverse and industrial metaverse (*i*Metaverse) platforms. Social metaverse deals with a network of virtual worlds focused on social connections, entertainment, and commerce, such as the metaverse pursued by meta.[4] The *i*Metaverse, on the other hand, integrates information and communication technologies related to industrial processes creating rich digital twins that blend real-world elements contextualized with meaningful digital data. While the use of technologies, such as virtual and augmented reality, digital twins, and artificial intelligence (AI) is opening new ways to aggregate and display information for industrial decision making, collaboration, and keeping processes running at peak efficiency, some key challenges remain to be solved to make the vision of an *i*Metaverse reality.

"WE PROPOSE TO USE KG TECHNOLOGIES TO SUPPORT INTEROPERABILITY AND SEAMLESS TRANSFER OF INFORMATION ACROSS IMETAVERSE PLATFORMS. WE DEVELOPED AN IMETAVERSEKG BASED ON AN EXEMPLARY USE CASE FROM DESIGN AND ENGINEERING APPLICATION."

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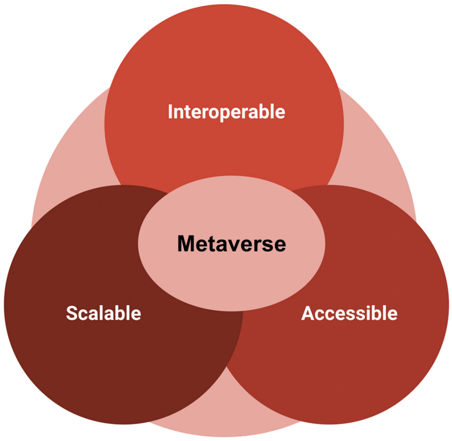

FIGURE 1. Characteristics of metaverse: interoperable, scalable, and accessible.

Today many industrial processes, e.g., design and engineering, testing, validation, manufacturing, or operations, are taking place in their silos with little information exchange across different processes. To build *i*Metaverse environments that facilitate use cases from these domains, we need to assure interoperability across platforms and software tools used today. We propose to use knowledge graph (KG) technologies to support interoperability and the seamless transfer of information across *i*Metaverse platforms. We developed an industrial metaverse knowledge graph (*i*MetaverseKG) based on an exemplary use case from design and engineering application. In this article, we present the characteristics of the metaverse, *i*Metaverse and its challenges, and the *i*MetaverseKG for an exemplary *i*Metaverse application from the design and engineering domain.

We propose to use KG technologies to support interoperability and seamless transfer of information across *i*Metaverse platforms. We developed an *i*MetaverseKG based on an exemplary use case from design and engineering application.

METAVERSE CHARACTERISTICS

Metaverse platforms are characterized by interoperability, scalability, and accessibility (see Figure 1).

Interoperability

Metaverse environments keep the records of virtual items by a user enabling seamless transfer of items across different virtual environments. A virtual item brought by a user into one virtual environment can be easily transferred and used in another shared virtual environment within a metaverse, allowing interoperability across environments. Unlike the physical world, there is no wall between virtual worlds.

Scalability

The metaverse allows several virtual avatars to coexist on the platform. There is no restriction on the number of virtual items in the metaverse. Real-time events hosted in the metaverse allow unlimited audiences. The users can attend virtual events from anywhere in the world hosted on a server without sharing their personal servers. This provides user interaction across various shared virtual environments. The scalability characteristic of the metaverse is hugely beneficial for sports events, live concerts, educational institutes, and collaboration with rich online content libraries.

Accessible

The metaverse does not have many access restrictions and allows accessibility of live reality in real time. The metaverse may not have a hardware restriction and can be accessible to all devices. The virtual environments in the metaverse have no cost restrictions, no building codes, and no development glitch to consider. The companies, artists, and influencers can create their virtual limited-edition exclusive virtual assets for their users. The technology platforms to create interactive content are evolving rapidly. It has endless virtual opportunities for everyone. The metaverse is recognized as a workplace where people can invest, buy, and lease their virtual assets.

INDUSTRIAL METAVERSE

The *i*Metaverse aims to promote the development of manufacturing and services for the industry. It can simulate the physical reality of interest to the industry, such as the product cycle, collaboratively designing a product, working with a client, visualizing the product, and optimizing the design. Typical drivers are to achieve better efficiency, discovery, and innovation. The process saves computation, material cost, product development, and client feedback time and meets market needs faster. Manufacturing companies, such as BMW, use *i*Metaverse-based augmented virtual reality to advance the design and prototyping of a new product.[6] The product design involves visualizing and interacting with the design in the *i*Metaverse environment. It allows simultaneous design review, updates, and assembly checks in real time before putting the design into production. The engineers can visualize their computer aided design (CAD) model and work collaboratively with the customers and other teams across different locations. The *i*Metaverse aims at lowering the production costs and improving time to market.

The *i*Metaverse has the following five key facets, as shown in Figure 2.

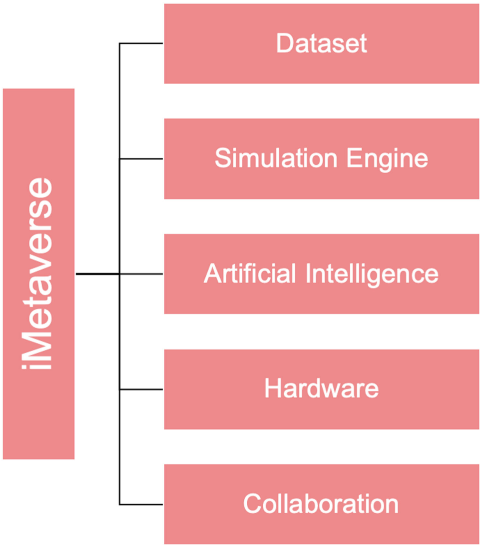

FIGURE 2. Key facets of *i*Metaverse: Dataset, simulation engine, AI, hardware, collaboration.

- Dataset—information from Internet of things (IoTs) devices, enterprise, Internet, human social interactions, etc.
- Simulation engine—provides the rendering and computing capabilities to support the physical world and real-time interactivity in the *i*Metaverse.
- Artificial intelligence—the AI and big data technologies provide perception and cognitive capabilities, such as learning, creating, and optimization.
- Hardware—intelligent interactive devices with capabilities of real-time integration of physical and virtual world, such as IoTs, new materials, general purpose hardware, and robots.
- Collaboration—interoperability, openness, and compatibility are the core elements for providing a better user experience in the *i*Metaverse. The intercompany and interindustry collaboration will increase *i*Metaverse content and value, promoting an open and collaborative ecosystem for *i*Metaverse development.

CHALLENGES

Just like HTML protocols created a unified framework for web pages on the Internet, enabling browsing the Internet from any device and browser. The operating systems, such as android, iOS regardless of having different devices, can still connect and exchange information among themselves. The software and application developers can implement their products on both platforms with minimal effort. The *i*Metaverse devices and platforms need to deliver such capabilities to users and content providers alike. The *i*Metaverse is in its initial stages. The biggest challenge it faces is interoperability between platforms.[7,8,14,15] Currently, there is no developmental standard in the metaverse. As a result, the information, and data necessary to model the real world in a virtual environment are scattered across multiple platforms leading to different platforms requiring different hardware and software. An *i*Metaverse can be created with various platforms, including NX, AutoCAD, Simcenter STAR-CCM+, Plant Simulation, Unity, Autodesk, and the Nvidia Omniverse. These platforms often use different data models and terminologies to describe the same thing, making it challenging to connect data even if it has been aggregated in a single data file. In addition, there is a need for real-time interactivity synchronization across different platforms. The edits made in one platform or product cycle should seamlessly communicate or transfer to the other platforms. As depicted in the left side of Figure. 3, present, describes the current single tool-to-tool interactions, which lacks scalability and is a time-consuming process, requiring teams of diverse technical backgrounds to work together closely and involves several iterations of the tool before production ready. On the contrary, the right side of Figure. 3, future, describes the proposed *i*MetaverseKG for interoperability and scalability where adding data and tools from a new tool is a seamless integration process, which simply requires adding a KG link to the new tool's data representation.

In the following sections, we will drill down the interoperability issue and its solution using KGs in the engineering and design applications for the *i*Metaverse.

*I*METAVERSEKG: *I*METAVERSE KNOWLEDGE GRAPH

A KG captures the complexity of the real world and stores information intuitively. KGs are more flexible than traditional relational data models making it easy to add, edit, and remove data to respond to real-world changes. The current *i*Metaverse description is semantic free, solely relying on the geometric artifacts of the virtual environment. We propose an *i*MetaverseKG, a semantic network of meta-data entities and their relationships, which enables seamless representation from the physical world into the virtual *i*Metaverse. It functions as a connective platform between diverse systems, promoting interoperability, and fusing data across different tools. It connects

METAVERSE: UNADDRESSED CONCERNS

Like other technologies, the metaverse is no exception to issues of abuse, security, trust, privacy, regularization, human interaction, etc. The laws of the physical world do not span to the metaverse. Digital avatars in the metaverse environment could be a victim of not physical but mental and emotional trauma due to online abuse. There is no legal framework to deal with digital misconduct and crimes. Content creators need licensing and usage boundaries to create avatars that create commercial value. There would be disputes regarding the metaverse's commercial value and intellectual property.[1] Grungo Colarulo is a startup that deals with laws and regulations about digital avatars in the metaverse. It proposes an AI-driven digital lawyer in virtual space, providing services, such as resolving digital land disputes, virtual legal firms, and company incorporation.[2]

The responsible development of the metaverse cannot be done single-handedly by one company. The safe development of metaverse requires the close collaboration of developers, industry partners, experts, and policymakers. Each metaverse platform requires configuration of its own and lacks a standard development format. Metaverse standard forum, a nonprofit organization, with 35 founding members and over 1500 partners from industries and academic institutions, are working together to develop standards for building an open and inclusive metaverse. EVERFI, an education company, designed a metaverse digital literacy curriculum, "Get Digital: Safety in the Metaverse," to empower students with the digital citizenship skills needed for safe metaverse usage.[2] In addition, Australian National University and professor Genevieve Bell are working together to develop an approach to "system by design," which industries can adopt for metaverse development.[2] Another example domain is music, where HiiWAV invites black musicians to equip the black, indigenous, and people of color with skills needed for metaverse development.[2] Also, youth organization, such as Youth Bureau, brings together technology companies, youth, and policymakers in the early development of metaverse and societal response for extended reality technologies with the inclusion of youth, promoting early engagement, and safe and inclusive development of technology.[2]

The KG has successfully aided in the issues of safety, toxicity, and human interaction in a community. For example, in the past, KGs have been used for 1) detecting hate speech and toxic content on the Internet, which often requires understanding the background knowledge, context, language, etc., 2) community detection using the interactions and characteristics, 3) detecting software security entities, such as software weakness, attack pattern, vulnerabilities, etc., which are scattered across various documents, 4) processing and analyzing cybersecurity data with fragmented multiple threat data and industrial network framework to identity cybersecurity entities and relations between them.[3,4,5,6,7,8] Metaverse development is a continuously evolving space with opportunities for improvement for its safe usage.

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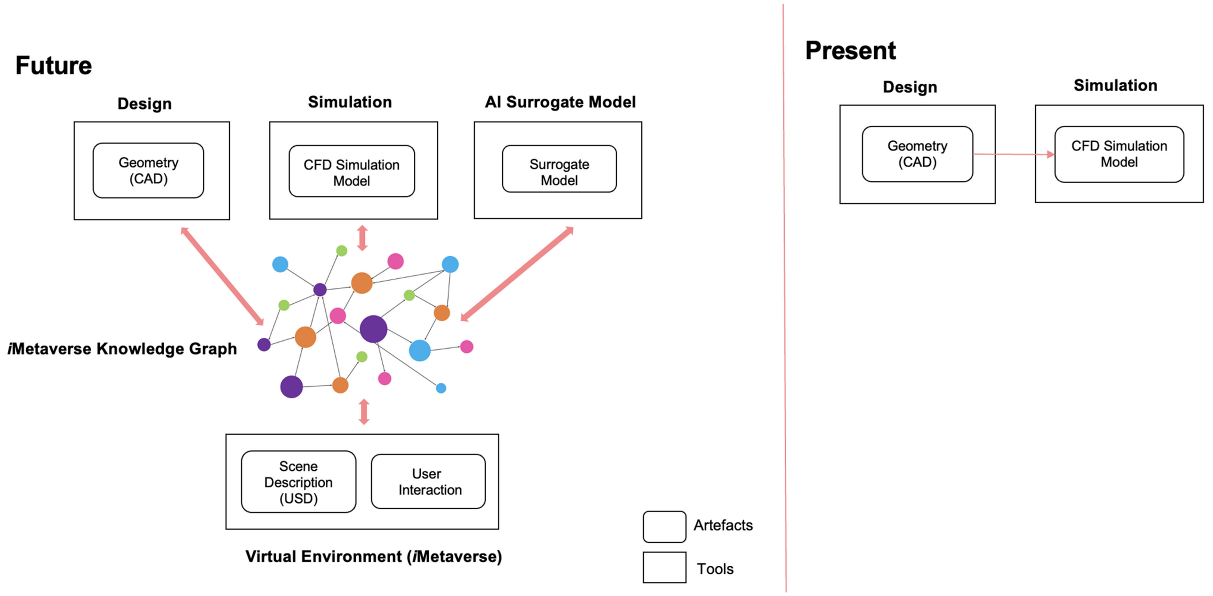

FIGURE 3. Shift from the current engineering and design approach to the future approach for the use of *i*Metaverse incorporating *i*MetaverseKG. (Abbreviation: CAD—Computer aided design, CFD—Computational fluid dynamics, AI—Artificial intelligence, USD—Universal scene description).

these platforms, standardizing concepts at a semantic level so they can be applied across the *i*Metaverse development pipeline.

The *i*MetaverseKG 1) describes the relationships and semantics of *i*Metaverse entities and tools, 2) bridges the gaps across *i*Metaverse platforms, 3) standardizes the concepts that can be applied across the *i*Metaverse development pipeline, and d) promotes the reusability of metaverse entities in a new platform or environment. The seamless integration of semantic information in *i*MetaverseKG enables synchronization across platforms. The updates made by user interactions or design changes do not require a new design and development iteration. The updates can be seamlessly integrated into the design steps by running a few update queries to the *i*MetaverseKG. The updates can be transferred, and the user interaction or the design changes can be assimilated according to the new updates.

We will discuss the use case of the *i*MetaverseKG in the *i*Metaverse for designing a computational fluid dynamics (CFD) simulation of a car in a wind tunnel.

ENGINEERING AND DESIGN IN *I*METAVERSE

CFD is a branch of fluid mechanics that solves problems involving fluid flows using numerical analysis and data structures. It solves engineering problems in applications, such as aerodynamics, weather simulation, industrial system design and analysis, fluid flow, and heat transfer. It simulates free-stream flow and the interaction of the fluid with the surfaces (defined by boundary conditions). The forces acting on the fluid body and the changes in the internal fields, such as pressure, velocity, density, and temperature can be mathematically expressed using Navier Stokes differential equations.

The CFD simulation process involves formulating the flow problem; modeling the geometry and flow domain in which the flow will be simulated using CAD; establishing the boundary and initial conditions of the system; generating a discretized grid of the flow domain; establish the simulation strategy, such as choice of turbulence model, and algorithms; establish the input parameters; perform the simulation with iterative, batch or distributed processing; monitor the simulation for convergence; postprocess the simulation to get the desired flow properties; compare the computed results from experimental computational, or analytical studies to establish the validity of the computed results; and repeat the process to understand the differences in the accuracy and performance of the computed results.[10] The CFD simulations often take 10+ hours to solve the differential equations on GPU clusters.

The time complexity of the CFD simulation can be overcome by explicitly exploiting the physics underlying the fluid flow at a given time and space. This

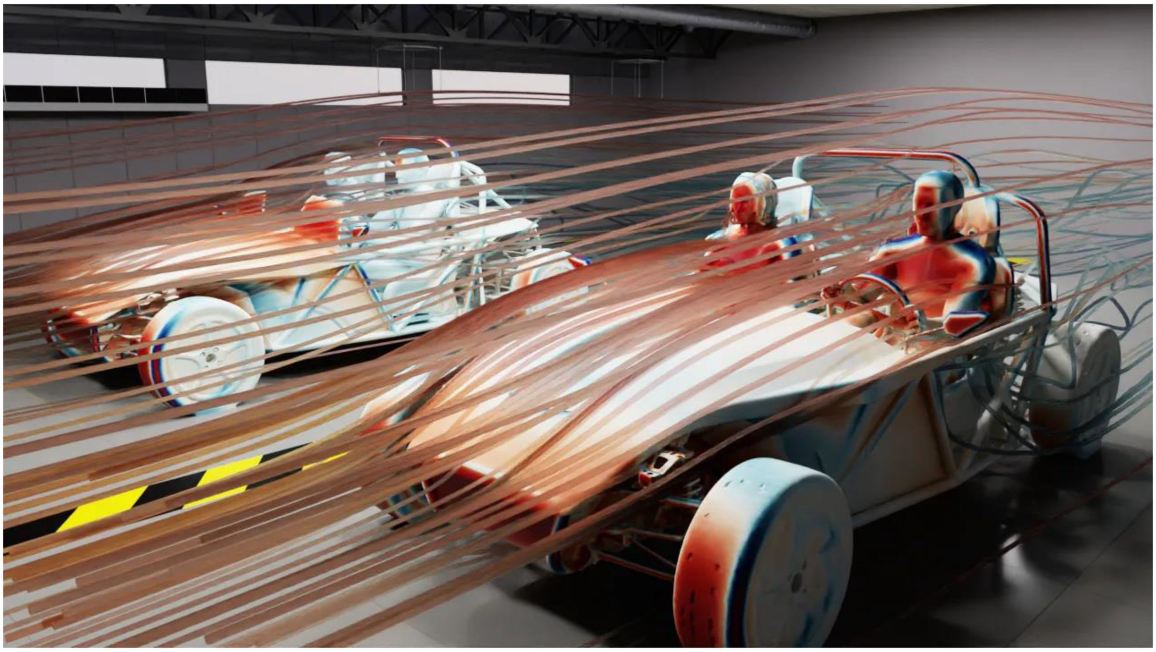

FIGURE 4. Exemplary visualization of velocity and pressure fields from 3-D steady state CFD simulation done in Simcenter STAR-CCM+ around two exemplary car configurations and its passengers, rendered using Nvidia Omniverse.[9]

technique is known as AI-Surrogate models, which utilizes physics inspired neural networks.[11,12,13]

We design a CFD simulation of aerodynamics flow around the car in the *i*Metaverse. The design steps includes 1) designing the geometry of the car using the CAD, and universal scene description (USD) framework by Pixar. The USD framework facilitates the visualization of the car in the *i*Metaverse, 2) running the CFD simulations using the state-of-the-art simulation tools, such as Simcenter, 3) running the AI-surrogate model-based CFD simulation for near real-time simulation, and 4) visualization in the *i*Metaverse. Figure 4 shows the metaverse visualization of testing of the CFD simulation of two different designs (geometry) of the car in the wind tunnel. It shows the effect of the wind on the passengers in the cars with varying configurations, with windshield (see Figure 4, car at the back), and without windshield (see Figure 4, car in the front). The *i*MetaverseKG captures the semantics, and the metadata entities incorporated in the design steps mentioned previously leading to better interoperability and reusability. It provides a platform for the standardization of concepts in the *i*Metaverse development. The *i*MetaverseKG (a representative subset is shown in Figure 5) gathers the meta-data entities included in designing the geometry of the car in CAD for CFD simulation, boundary conditions for CFD for the simulation and surrogate models, and entities capturing the geometry and visualization of the CFD in the *i*Metaverse to be visualized using a USD framework for scene visualization.

The *i*MetaverseKG also defines a metaverse instance, which has an instance of a car. A car in the wind tunnel, as shown in Figure 4, can be represented by both CAD and USD geometry. The CAD geometry for CFD simulation and USD for *i*Metaverse visualization. The USD geometry is derived from the CAD geometry. The CFD simulation models take CAD geometry as input. The *i*MetaverseKG also captures the boundary conditions used for simulation and surrogate models, ranging from 0 degree to 180 degree of wind direction, and 0 to 80 km/hr of wind speed for the example use case. Figure 5 considers the boundary condition of 30 degree wind direction and 20 km/hr wind speed for CFD simulation, and 0 degree wind direction and 60 km/hr wind speed for AI surrogate for a given instance of car with a particular CAD and USD representation.

An instance of a car can be subjected to different boundary conditions resulting in multiple CFD simulations and surrogate models (Figure 6 shows an example use case for a single wind speed and wind direction). The *i*MetaverseKG captures the abovementioned meta-data from different tools and provides a platform for interoperability, synchronization, and standardization. The real-time visualization of the aerodynamics flow in the *i*Metaverse requires fetching the geometry of the car, CFD simulation, and AI-surrogate models for each boundary condition,

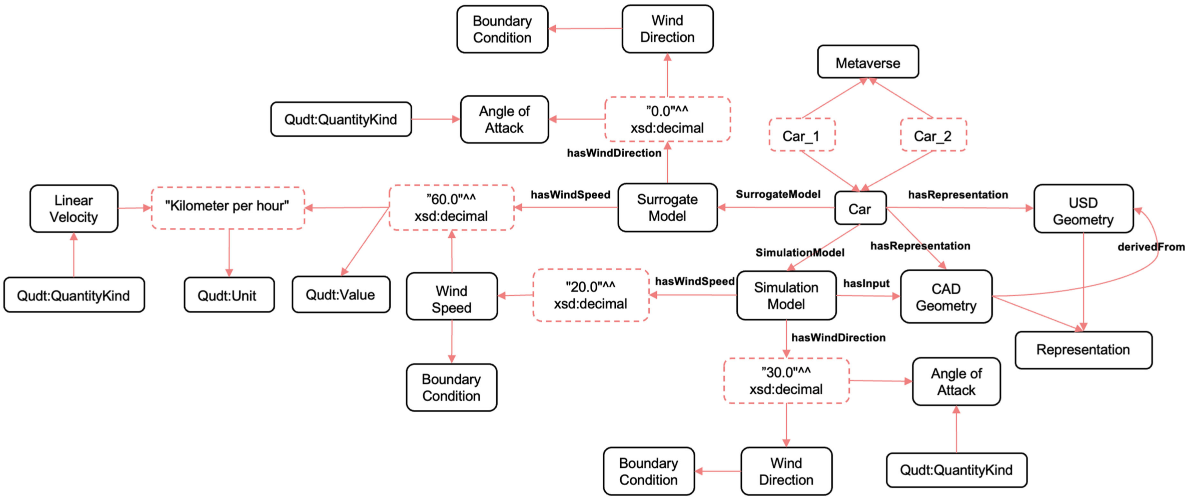

FIGURE 5. Snapshot of an *i*MetaverseKG focused on a CFD simulation of a car in the *i*Metaverse. The *i*MetaverseKG provides a standardization platform, which captures the information about the design steps along with the meta-data entities describing the geometry (design) of the car, and the surrogate and simulation models used in the CFD.

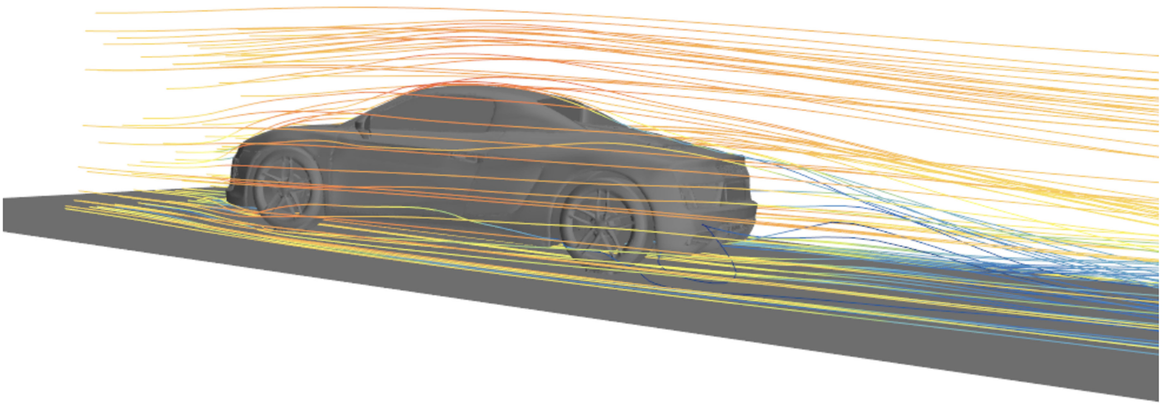

FIGURE 6. Instance of a car with a given geometry representation an *i*Metaverse for a single boundary condition with a given wind speed and wind direction.

which have been stored in the *i*MetaverseKG. The *i*MetaverseKG promotes reusability of the instance of the car, as shown in Figure. 5, which can be modified as well as reused in a new *i*Metaverse environment. It can be used to study the difference of aerodynamics around the car in the tunnel, as shown in Figure 5, as compared to the car on a track, as shown in Figure 6. The *i*MetaverseKG stores the semantic scene description about the car, tunnel, and the track, which otherwise is missing in the current development pipeline. It can also assist in studying the effect of different material properties of the car on the aerodynamic flow, such as changing the car material from metal to ceramic. One can modify and visualize the different car geometry and aerodynamic simulations for a given boundary condition in real time in the *i*Metaverse. Modifying wind direction, and wind speed using the *i*MetaverseKG simply requires an update, synchronization, and retrieval query on the KG to fetch the appropriate model to run and visualize in the *i*Metaverse, which otherwise be time consuming requiring running a new simulation, and surrogate models and development of multiple tool-to-tool interactions from the CAD, USD, CFD simulations, and AI-surrogate model.

CONCLUSION

The issue of interoperability across metaverse platforms has been well recognized by the community,

ROLE OF KG IN STANDARDIZATION

KG has been widely used for standardization in the industrial applications ranging from finance, transportation, healthcare, education, remote operation and maintenance of equipment, intelligent computer-aided diagnosis, treatment, and so on. KGs have achieved success in auxiliary design, equipment operation and maintenance, supply chain management, etc. It helps represent information in a human understandable form, which enhances the ability to manage, organize, and understand the large amount of information. In 2019, the IEEE Knowledge Graph Working Group initiated projects IEEE P2807 and P2807.1. The IEEE P2807 standard project "Framework of Knowledge Graph" describes the requirement for input, construction process, performance metrics, applications, and infrastructure. The IEEE P2807.1 standard project, "Standard for Technical Requirements and Evaluating Knowledge Graphs," establish technical requirements, performance metrics, evaluation criteria, and test cases for KG. The test cases include input data, meta-data, data extraction, data fusion, storage and retrieval, inference and analysis, and KG visualization.[1] In the healthcare, KG integrates the heterogeneous information from textual medical knowledge from biomedical literature, with the healthcare information system. The healthcare system has a large amount of textual medical knowledge and patient healthcare information from clinician notes, which plays an important role in knowledge delivery and decision support to both clinicians and patients. With the growing amount of this information at a rapid pace it faces the challenge to organize, integrate, analyze, and deliver information in an efficient manner. The KG-based standardization framework for the abovementioned data facilitates faster query, update, and reasoning, as well as supports human and machine interpretability.[2] In the intelligent manufacturing, an enterprise KG integrates and systematize business data from different departments (such as market monitoring system, logistics traceability system, inventory management system, order management system, human resources management system, maintenance management system, and operation management system), and expert knowledge in different areas (such as fault repair, market forecasting, sales violation, and production scheduling), which leads to better decision making. Furthermore, the knowledge also assists in anomalies traceability in the production line by tracing back the corresponding node and analyzing the subgraph for the issues and possible solutions.[3]

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such as W3C and Metaverse Standard Forum.[7] The *i*MetaverseKG provides an ability for interoperability and integration across platforms in industrial engineering and design applications. The *i*MetaverseKG has an advantage over the existing tool-to-tool integration platforms for solving the interoperability issue. Furthermore, the current tool-to-tool integration development lacks scalability, whereas adding data from a new tool to *i*MetaverseKG is a seamless integration process requiring KG links to the new tool's data representation. Although the *i*MetaverseKG is still in its early stage, it has enormous potential to address the issue of interoperability and promote reusability in *i*Metaverse development.

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