The Cyber-Physical Metaverse - Where Digital Twins and Humans Come Together

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***Abstract*—The concept of Digital Twins (DTs) has been discussed intensively for the past couple of years. Today we have instances of digital twins that range from static descriptions of manufacturing data and material properties over live interfaces on operational data of cyber physical systems to the functions and services they provide. Currently, there are no standardized interfaces to aggregate atomic DTs (e.g., the twin of the lowest-level function of a machine) to higher-level DTs providing more complex services in the virtual world. Additionally, there is no existing infrastructure to reliably link the DTs in the virtual world to the integrated CPSs in the physical world, such as a car consisting of many ECUs with even more functions.**

The concept of the Metaverse is gaining increasing traction and has been explored from different angles, usually centered around a human user, true to its original definition. Beyond social interactions, the Metaverse offers possibilities to integrate layers of interconnected Digital Twins (DTs) representing parts of and interacting with the physical world in real-time, enabling not only analysis and representation of current state, but also feedback loops and control.

This paper describes how the Metaverse can become the virtual world where DTs of humans and machines live, and how to reliably connect DTs to the physical world.

***Index Terms*—cyber-physical systems, reliable distributed systems, real-time systems, cybersafety, metaverse, digital twins**

I. Introduction

The Metaverse has first been introduced in literature [1] as a virtual world for humans to interact. More recently, this term has been used for a new form of social network, connecting people around the world through Virtual Reality (VR). In some cases, this VR has in parts been overlayed with the physical world in the form of Augmented Reality (AR) or in full in the form of Mixed Reality (MR). In every case, the Metaverse is usually centered around humans interacting in this (partially) virtual world.

Cyber-Physical Systems (CPSs) are a class of systems interacting with the physical world, by observing (sensors) and influencing the physical world (actuators). The interconnection inherently contains a number of challenges, most importantly the lack of time alignment, as the physical world is operating in real-time and the CPS needs to follow suit. Furthermore, many applications of CPSs are required to adhere to strict safety requirements, as the influence on the physical world has the ability to endanger human lifes and thus correct operation or a fail-safe fallback need to be ensured.

In this paper, we are proposing the Metaverse for CPS, not only enabling interaction of humans with humans, but broadening the concept to include sensors, actuators, and physical machines, represented in the form of interconnected DTs. This Cyber-Physical Metaverse (CPM) need not and likely will not be distinct from the Metaverse humans are interacting in. However, the focus is rather on interconnecting devices to enable functionality, including those with real-time and safety requirements, on a scale never seen before.

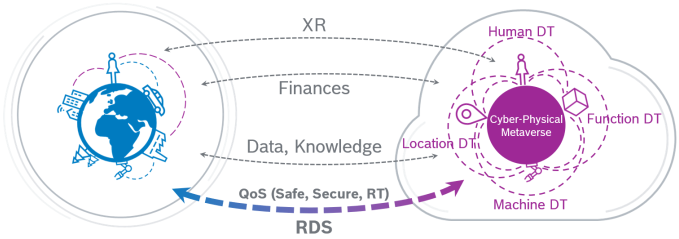

Fig. 1. The Cyber-Physical Metaverse and its linkage into the physical world

II. The Metaverse

Matthew Ball [2] describes the Metaverse as future state of the internet, a revolution of the infrastructure layer of the digital world as well as of the services and plaforms on top of them. According to his widely cited definition, the Metaverse will...

- *be synchronous and live* - This requires a notion of concurrency and synchronicity for spatially distributed agents. For a restricted number of users (typically a few hundred), this is realized already today in battle royal games or video chat applications.
- *offer unprecendented interoperability* - This offers a semantic linkage between agents and objects in the Metaverse, a mission pursued by the Metaverse Standards Forum [3] fostering interoperability standards.
- *be an experience that spans both digital and physical worlds* - Promising as it sounds for the vision of the CPM linking virtual and physical world, at least in [2] there are only limited links between the Metaverse and the physical world: humans and finances (cmp. Fig. 1).

These properties of the Metaverse are essential for supporting digital twins of CPSs in the CPM.

III. Digital Twin Applications

A Digital Twin (DT) is a concept of creating a virtual instance of a physical object or machine. Depending on their intended usage, DTs feature static manufacturing data, 3D models, live operational data, and in so called actionable Digital Twins even APIs to manipulate and control its physical twin.

There are many activities around DTs of production machinery, including simulation and visualization of DTs to, e.g., create a virtual staging area for new control programs of production robots. This is often coined as Industrial Metaverse, e.g., by NVIDIA who market there Omniverse [4] as a platform

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for creating and operating Metaverse applications, with a special focus on visualization. The Industrial Metaverse provides valuable insights to human operators and developers [5] but typically offers no direct link to control production processes in physical world.

Hyundai's concept of metamobility as presented at CES 2022 [6] advocates a new era of mobility by creating DTs of physical world locations where humans can virtually travel, and creates a link from the Metaverse into the physical world using robots as proxies. This way, you can remote control a consumer robot in a DT of your apartment to feed pets or water plant.

There are many further applications for actionable digital twins which are not only used for visualization and analysis but also for controling their physical twin. In its simplest form, actionable digital twins can be used offboard control intelligence from embedded devices (e.g., cloud robotics) in order to replace expensive compute resources on the device by cheap cloud compute.

This can be further enhanced by introducing centralized coordination services which have no direct physical machine equivalence but are rather a higher-layer DT servicing multiple DTs. This is envisioned as part of a push towards infrastructure-based automated driving and based on telecommunication network services, e.g., for 5G-enabled traffic flow simulation and situational awareness, discussed at the 3rd Generation Partnership Project (3GPP). These use cases benefit from fusion of distributed sensor inputs and from being able to coordinate and control multiple actors in order to achieve optimizations no individual agent could have achieved alone.

IV. The Cyber-Physical Metaverse

The CPM can be seen the next stage of evolution for a new generation of CPSs. The CPM is as a global abstration layer of things in the physical world and a runtime environment for services. It enables human-machine collaboration, as well as machine-to-machine collaboration, through interconnection of their DTs. This obviously requires standardized interfaces for the respective DTs.

Figure 1 shows the relationship of and links between the physical world and the CPM. Extended Reality (XR) is used to connect the human, through its avatar into the CPM. Note that a human is represented in the CPM by a human DT which extends the avatar with a continuously available independent agent being able to represent the human, interact with other DTs and take decisions on his behalf in a defined set of matters. The avatar is the live representation of the human in the CPM as well as the human's interface to its digital twin.

As in the Metaverse, data and knowledge are shared between the virtual and physical world. Additionally, financial flows exist between the physical world and the CPM, e.g., for usage fees of services in the CPM.

The key enabler for the CPM are Reliable Distributed Systems (RDSs) [7] as a technology to reliably link CPSs and their Actionable Digital Twins (ADTs) with a desired quality of service (QoS). This way, ADTs become the agents of CPSs in the CPM and are interconnected with further DTs to enhance their functionality. This makes ADTs the *API of the Future*, as they are the interface of CPSs to the CPM and form the basis for all enhanced functionality.

V. Research Challenges

One of the biggest challenges is to provide consistent and deterministic end-to-end real-time guarantees from physical machines in the real world to the CPM and back. This is evident, for example, when looking at computing platforms tuned for average performance and software stacks that result in long tail latencies in edge and cloud computing.

However, technology is evolving, and deterministic timing is becoming more of a central concern. Examples include techniques for network slicing and application-level resource management in 5G/6G networks as well as built-in mechanisms in computing platforms that enable performance isolation, such as Intel's Resource Director Technology [8]. What is missing is a common framework and abstraction that breaks down end-to-end application-level QoS requirements into individual QoS requirements for the hops involved along the cause-and-effect chain, as argued in [9].

Another key challenge is to provide safety guarantees in a distributed system that contains components that are not safety certified. But here, too, initial works [10] suggest that a distributed system with heterogeneous computing resources and a large number of different sensors allows novel redundancy patterns that support system-level safety arguments that were not possible on certified embedded hardware for cost reasons.

VI. Conclusion

In recent years, technology developed to the point in which the Metaverse is now a possibility. In addition, we are seeing a number of building blocks being available or under active research and development, allowing to integrate CPSs with the Metaverse into a Cyber-Physical Metaverse (CPM) offering enhanced functionality and performance. There are, however, a number of research challenges remaining, such as real-time and safety guarantees for mixed-criticality systems in the cloud. Furthermore, the interfaces between different layers of DTs need to be standardized and already existing building blocks need to be integrated into a platform, the CPM.

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