Chapter 11
IoT Blockchains for Digital Twins

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ABSTRACT

Digital twins (DTs) have emerged as a critical concept in cyberspace infrastructure. DTs are virtual representations of physical things including model smart structures or environments, manufacturing processes, humans, and a variety of other things. The value provided by DTs relies on their fidelity in representation. Blockchains provide trust assurance mechanisms, particularly where multiple parties are involved. The expected life cycle operations of the IoT, blockchain, and DT need to be considered to develop economically useful blockchain digital twin (BDT) models. BDTs do not exist in isolation, but rather within a DT environment (DTE). A DTE may include multiple DTs of different objects to enable interactions between these objects to be evaluated in both virtual reality and mixed reality cases. To populate DTEs with multiple DTs requires industrialized tooling to support the rapid creation of DTs. The industrialization of DT creation requires frameworks, architectures, and standards to enable interoperability between DTs and DTEs.

INTRODUCTION

Digital Twins (DTs) are digital representations of living or non-living physical objects. DTs have been widely considered in the context of manufacturing as a conceptual model in the product lifecycle management process (Grieves, 2019). Digital modelling in manufacturing combines computer aided design techniques (e.g., 3D models) with additive or subtractive manufacturing processes. ISO defines a DT in manufacturing as *a fit for purpose digital representation of an observable manufacturing element with a means to enable convergence between the element and its digital representation at an appropriate rate of synchronization* (ISO 2021). A DT can also be considered as a projection of physical objects into digital spaces e.g., virtual reality. DTs can also be used to optimize asset performance through monitoring, diagnostics, or prognostics (Tao et al., 2018). In the context of the built environments, DTs have been used to capture spatial data capturing the building, smart city, etc. (Deng et al., 2021). DT

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technologies can also model living organisms, including humans. Human DTs (HDTs) are emerging for healthcare (Croatti et al., 2020) and social interaction. A broad range of applications for DTs and related technologies has led to a broad range of definitions for DTs (See, e.g., Minerva et al., 2020 and Voas et al., 2021). All DTs rely, to a greater or lesser extent on sensing operations (typically based on IoT devices) for the creation and operation of the DT. Blockchain Digital Twins (BDTs) are a subset of the DTs that incorporate blockchains to provide additional trust-based features.

The connectivity between the physical object and its DT is one of the main characteristics of DTs. A *static* digital twin only requires connectivity with the physical world (1) when the digital twin is created as a digital model of the physical object, or (2) when the DT is used to drive some physical process (e.g., manufacturing replicas of a scanned physical object- model based manufacturing). A *dynamic* DT maintains a digital representation of the current state of the physical object. The current state of the physical object is typically characterized using IoT sensors. This DT - Physical object connectivity, whether for model creation or state maintenance, is a form of machine- machine communication. 5G and 6G networks provide additional capabilities to support machine-machine communication. The ITU-T recognized DTs as a use case driving additional requirements for 6G features (ITU-T, 2020). Maintaining the linkage between the DT and physical world requires continuous connectivity between the DT and the Sensors monitoring the physical object's status. For a movable physical object, these sensors either need to be attached to the object or the range of motion needs to be constrained. The integrity and trustworthiness of the DTs as representation of the physical objects' current state relies on the authenticity of the data as well as the modelling process.

The connectivity patterns of digital twins differ from typical human communications or web browsing. The IoT sensors are clustered sensing the physical object and its physical environment in a specific locality. The DT and the Digital Twin Environment (DTE) where the DT executes may be localized in some manufacturing 4.0 scenarios to reduce latency from the modelled physical objects. Other use cases may provide significantly greater value if the DT can be executed in a remote DTE. Early approaches to the DT concepts, systems, and technologies, typically leveraged the prevalent centralized computing system architectures. As DTs start to move from research concept and implementation prototype to commercial deployments, they are being to be applied to problems that matter to people. As commercial users of DTs come to rely on those models, it becomes more important to ensure the data provenance, audit, and traceability in the creation of the DT model as well as its operation (Hasan et al., 2020). Not only the data from the original physical object, but also the data from the DT – transactions, logs and history - need to be secure and tamper-proof. Decentralized connectivity patterns and blockchain architectures can provide lower risks than centralized architectures. Commercially successful DTs are likely to be operated by multiple independent users that trust in the proper operation of the DTs. Such users' objectives may also require the trustworthy operation of more than one DT, where some DTs come from different sources to execute in the same DTE.

For users of DTs to benefit from this digital representation, they must trust that it provides an adequate representation for their purposes. For a static DT, this requires trust in both the modelling process and the underlying data; dynamic DTs obviously add temporal considerations. Many early DTs were developed within a single organization. As the technology becomes more widely deployed, multiple parties are likely to be required. DT models of components in a supply chain context may be independently developed by the respective component manufacturers but required for use by the downstream users of those components. Privacy is also a concern for commercial uses of DTs. The physical objects modelled by the DT may include intellectual property (e.g., trade secrets). The owners of the physical objects

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