A Simulation Based Approach to Digital Twin's Interoperability Verification & Validation

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Abstract

The digital twins of production systems are one of the pillars of the Indus-try of the Future. Despite numerous on-going research and development initiatives the verification and validation of the digital twin remains a major scientific obstacle. This work proposes a simulation-based approach to achieve this goal: support Digital Twin verification and validation through the definition of a dedicated framework. A simulation model is used in place of the real-world system for ensuring the digital twin behaves as expected and for assessing its proper interoperability with the system to be twinned with. Then the simulation model is replaced by the real-world sys-tem, to interoperate with the verified and validated digital twin. With such an approach, the interoperability middleware, i.e. the IoT between the sys-tem and its digital twin can also be modeled, simulated, verified and vali-dated. Consequently, an optimized solution can be built for an entire value chain, from the system to its digital twin and conversely.

Keywords

Digital twin, verification and validation, simulation.

1. Introduction

The concept of “smart everything” is emerging with the ever-growing digitalization of the society, from industrial and health sectors, to educational an urbanization sectors. Consequently, new production systems are appearing, where data and virtual technologies occupy a prominent place. Such systems are so complex that their management requires model-based approaches.

The digital twin (DT) concept has surfaced as such an approach and is landing in top strategic technology trends. It is based on the idea that a model which is used in different ways in place of a system of interest, is continuously synchronized with that system in order to reflect any real event happening to the system on the model, such that any management initiative can be assessed on this ever-updated artifact before transferring it to the system. Therefore, the model is more than a simple representation of the system, but a digital counterpart which is specifically bound to the system, rather than representing a family of systems of the same kind.

NASA is a pioneer in the system-pairing approach for having simulated from the ground situations occurring in space, to guide astronauts. Yet while this approach brought the Apollo 13 crew back safe in 1970, it didn't use a DT, but a pair of physical twins (respectively located in space and in ground).

The term digital twin first appeared in [1], and the underlying principle of a digital informational construct created as a separate entity and related to a physical system of interest was foreseen in [2]. In the context of product life cycle management, the model of a conceptual ideal was proposed and called Mirrored Spaces Model [3], and later Information Mirroring Model [4], and actually Digital Twin [5]. It has been defined as: "a set of virtual information constructs that fully describe a potential

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or actual physical manufactured product, from the micro atomic to the macro geometric level" [6]. This data-centric definition contrasts with the behavior-centric one given in [7], where a DT is "an integrated multi-physics, multiscale, probabilistic simulation of an as-built vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its corresponding flying twin".

From a simulation perspective, the DT is a disruptive approach, as simulation experiments are based on current information provided by the system, rather than assumptions [8, 9]. Used in this way, the DT serves both for representational purposes, and prediction-making on system behavior [10], which often appear as a set of integrated sub-models that reflect different system characteristics [11]. Some additional aspects have also emerged, such as DT-based prognostic and diagnostic activities [12, 13], as well as DT-based real-time optimization [14, 15].

Current DT applications span from automotive [16], avionics [17], aerospace [7], energy [18] to manufacturing [8], healthcare [19] and services [20]. Industrial applications of DTs include controlling the predictive maintenance of equipment, improving assets safety and reliability, and optimizing process operation and product design. In healthcare, the DT approach holds the promise of designing personal and completely tailor-made treatments/surgeries for diseases, in contrast with traditional approaches that are based on what is best on average for a large group of patients. DTs also allows servitization by supporting companies in monitoring their products while they are in customers' hands.

Despite all these research and development initiatives, DT verification and validation (V&V) remains a major scientific obstacle. This paper proposes a candidate framework to achieve that goal. It suggests a simulation-based approach, where a simulation model is used in place of the real-world system for ensuring the DT behaves as expected and for assessing its proper interoperability with the system to be twinned with. Then the simulation model is replaced by the real-world system, to interoperate with the verified and validated DT. With such an approach, the interoperability middleware, i.e. the IoT between the system and its DT can also be modeled, simulated, verified and validated. Consequently, an optimized solution can be built for an entire value chain, from the system to its DT, and conversely.

The remaining of the paper is organized as follows: We first propose in Section 2 a unifying framework to DT understanding and engineering. Then, Section 3 presents the V&V approach based on this framework. A conclusion is given in Section 4.

2. Unifying DT framework

The DT concept is approached by different professional communities in a way akin to the metaphor of a group of blind men who have never encountered an elephant before and who conceptualize what it is by touching it. Each blind man feels a different and unique part of the elephant's body. They then describe the elephant based on this sole experience and their views differ radically. Similarly, actors from different communities make various use of the term Digital Twin in a way that raises the issue of its fair and formal definition. Nevertheless, we argue that all these various DT views fall under the same common umbrella, which we try to formalize here.

2.1. Definition

What makes a digital model a DT is that there is a data-based synchronization between that model and the real entity of interest (be it a product, a process or a system) that the model represents, where data are collected from the real entity. We formally define the Twin of Interest (TOI) as referring to an entity of interest, viewed from a systemic perspective (i.e., a product/service/process system). Since the entity of interest can be material or immaterial (such as a software), the term TOI is preferred to "physical twin" or "real twin". We define a DT as referring to a digital abstraction synchronized with a TOI and reflecting one or more of the TOI's aspects (static, dynamic, functional, etc.).

2.2. Operational value chain

The value chain shown in Figure 1 defines a DT system that achieves rationality: (1) sensing its associated TOI, and collecting, cleaning, interpreting and storing data; (2) turning data perceived into capability models, i.e., data-based diagnosis/prognosis model, simulation-based prediction model, 3D-based visualization/monitoring model, and/or rule-based decision-making model that may combines other models; then (3) acting accordingly (the decision can be automatically derived and sent to the TOI to be executed by its actuators, or made by a human operator through a decision interface).

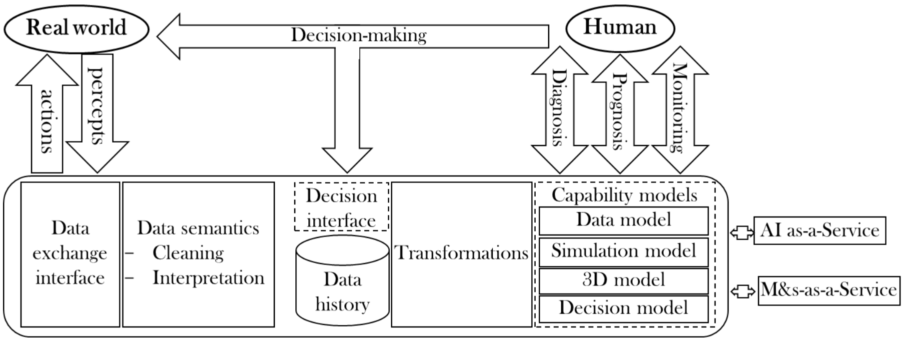

Figure 1: DT value chain's operational architecture.

The capability models are executed by engines embedded in existing as-a-service platforms, such as Analogic Cloud for simulation and AI4EU for AI (https://www.ai4europe.eu/).

3. DT V&V

The objective of this section is to suggest a systematic simulation-based DT engineering approach. We first propose an operational architecture, which we use to design the DT V&V methodology.

The role of the real-world system is played by a simulation model during the design stage of the digital twin, and the IoT infrastructure is simulated by an analogical model; once the digital twin realized and effective, the simulation model is replaced by the real system, and the analogical model by the real IoT infrastructure. Therefore, the V&V methodology's components are the following: (i) the TOI, i.e., the real system; (ii) the simulated TOI, i.e., a simulation model of the real system with implementation using the Anylogic software [21]; (iii) the simulated IoT, i.e., an Internet-based infrastructure that links the simulated TOI to its digital counterpart; and (iv) the DT, i.e., an instance of the operational architecture.

The V&V methodology consists in the following 5 steps:

1. Firstly, the simulated TOI is built and validated against the real system, using traditional V&V techniques [22].
2. Secondly, the simulated IoT is modeled and integrated to the simulated TOI, using an existing Internet-based mechanism (such as files shared in a drive on cloud).
3. Thirdly, the DT is built as a technology-specific instance of the layered model, integrating the communication with the simulated IoT.
4. Lastly, the DT operationality and interoperability are verified and validated against the simulated TOI, using traditional V&V techniques.
5. The validated DT is ready to be paired with the TOI, provided the simulated IoT is replaced by the real-world IoT, and the communication mechanisms implemented accordingly.

4. Conclusion

This work proposes a framework to support digital twin verification and validation. With it, a candidate DT must meet each of the following criteria in order to be qualified as a DT (if one of the criteria is not met, then the candidate is not a DT from our framework's perspective):

- A DT is a digital model of a reality, and is paired with that reality in a way it is able to self-update in response to known changes in the state, condition, or context within the reality represented. A model turns into a DT only when it is paired with its real counterpart. It is no longer a DT at the real counterpart disposal, as it turns to a digital documentation (unlike in Grieves's view where the lifecycle of the DT continues beyond the disposal of the real counterpart).
- A DT is uniquely paired with a specific instance of the reality and can contain various representations of that instance. The model(s) composing the DT can't be the twin of more than one real instance, regardless of their similarities in structure and behavior.
- A DT provides services (such as analysis, optimization, prediction, etc.) through capability models (such as visualization model, simulation model, etc.).

We propose an operational architecture, which technology-agnostically concretizes a DT reference model, and which allows us to define our V&V strategy. The methodology consists of replacing the twin of interest as well as the twinning middleware (the IoT) by simulation models, and when the digital twin is realized and tested against these simulated components, the real-world infrastructure is set, including the real-world system and the real-world IoT infrastructure. The framework has been demonstrated on various technology-specific use cases.

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