Digital Twin Engineering

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Abstract. Digital twins make use of numerous models during to design, deployment, operations and maintain Cyber-Physical systems and have received significant uptake in industry and academia. However, the engineering of digital twins themselves is a difficult task that has attracted more attention in the last years. This short paper introduces the ISoLA 2024 series of papers on the engineering of digital twins, with a focus on the connection to data-driven approaches, interoperability and adaptation to changes at runtime.

1 Introduction

Digital twins (DTs) are nowadays a well-established concept for cyber-physical system (CPS) engineering. They gain more and more interest both in research but especially also in industry [22]. DTs are considered a cornerstone of Industry 4.0 [20] and Industry 5.0 [17]. They are used in many application domains ranging from smart cities [19], smart buildings [12,1], to health care [13] etc.

Digital twins are an approach to model-based design, development, operations and maintenance for Cyber-Physical systems and thus support besides their development also their evolution. DT combine ideas from numerous lines of ideas, from model-based control and control theory, over knowledge representation and simulation, to software engineering and runtime monitoring. After significant advances in the last years, witnessed by several studies and first textbooks that structure the field, the research area is consolidating and we can see applications in evermore domains.

At the core of the digital twin approach is a physical entity (PE) and a corresponding digital entity (DE) that models the PE. Following Kritzinger et al. [14], the digital entity is a digital shadow if the model is (only) fed live data from the PE, and a digital twin if it communicates commands automatically back to the PE. To engineer a digital twin system, however, is more than merely connecting a model to the PE. It requires careful modeling of the system for a specific purpose, but also support for the entire life cycle of the twin.

While the concept of DT has gained of lot of attention in industry, the efficient realization as well as support for the evolution of DT is still active research. One prominent approach is Digital-Twin-As-A-Service (DTaaS), which aims at providing pre-engineering building blocks for DTs which may be orchestrated together to realize the DT in question [21]. The approach especially supports the design and operation of DTs. It builds on commonly available tools in the fields of message passing, databases, and especially simulation frameworks. The Function-Mock-Up-Interface (FMI) has gained popularity to provide a well-defined interface between simulation models based on differential equations and CPS [10]. Note that the FMI interface can equally be used when machine-learning based models are used. See [8] for an overview of open-source frameworks for building DTs.

For supporting the evolution of DTs, it is important to identify typical phases along their life time. According to [21], a DT life cycle consists of *create*, *execute*, *save*, *analyze*, *evolve* and *terminate* phases. Users might choose to create a new DT or select an existing DT.

The *create* phase involves asset selection and an specifying DT configuration. The *execute* phase involves an automated execution of a DT based on its configuration. The *save* phase involves saving the state of DT to enable future recovery. The *terminate* phase involves stopping the execution of the DT and releasing all the resources and connections mentioned in the DT configuration.

The typical operational phases are *create*, followed by *execute*, followed by either *save* or *terminate*. However, typically, a DT is evolving over time, which is reflected in the *analysis* and *evolve* phases. The *analysis* phase deals with estimating the state the DT is in, for which, typically monitoring of the PE is used. However, often many measures are not observable, meaning that many quantities are hidden. These are then estimated using (simulation) models reflecting the physical laws of the PE. The analysis may spot directly deficiencies of the DT resulting in direct evolution requests. However, typically, the analysis phase consists of a so-called *what-if analysis* which analyses minor to major variations of the DT to plan and optimize future steps to be undertaken either on a PE or a DE. Actual implementation of a what-if analysis can be resource intensive with the resource requirements scaling up in proportion to algorithmic bounds on the (sub)-systems being used by a DT and may benefit from planning and optimization tools. In the evolve phase, the DT is updated thanks to collected insight of its analyze phase, meaning the DE and/or the PE is reconfigured or redesigned based on analysis results.

The research on DT has to be validated in practice for which insightful use-cases have to be considered. Use-cases range from large-scale publicly available living labs [11] to minor uses such as in a fire-fighter example [16], to fully verified incubators [23]. As for any engineering research topic, it is important to identify more accessible use-cases for further evaluation.

From the discussion above, we see that research topics for DTs cover models for PE, the engineering of DTs by orchestrating individual assets and twins, the linkage of PE and DE by monitoring, methods for the evolution of digital twins, and experiences by consulting use-cases.

This ISoLA track, following two previous iterations [6,7], presents five articles that discuss digital twins engineering from different perspectives. At time of writing, it is also planned that (a) the recent textbook [5] on this topic will be presented in an invited presentation, and (b) the yearly general assembly of INTO-CPS [15] is held as part of this track. We thank the reviewers and organizers of ISoLA for their help and support.

2 Contributions

Foundation Models for the Digital Twin Creation of Cyber-Physical Systems. Ali et al. [2] discuss the connection of digital twins, specifically their creation phase, to foundational models – machine learning models for generic patterns, trained on vast amounts of data. The authors discuss two possibilities of using foundational models. The first is to use generic foundation models to generate the digital model (or a capability) used in the twin. This can be done either by generating (part of) the simulation model, assisting the developer in the process through either co-piloting or offering advice and access to requirement document through a chat interface. The second is to fine-tune the foundational model, which then acts as the digital twin itself. Either, it can serve as the digital twin capability and implement the interactions with the digital twin model, or it can replace both digital twin model and capability as one component. The authors discuss advantages, disadvantages and perspectives for both possibilities.

Interoperability of Digital Twins: Challenges, Success Factors, and Future Research Directions. David et al. [3] discuss the future of digital twins from the strategic, technical, organizational and standardization perspectives, based on a panel discussion that took place at the 2023 Annual Simulation Conference. Dawn Tilbury discusses that many aspects of digital twins have roots in prior approaches, such as state estimators for control systems, and that there is a need to aggregate different models for the same component based on the current need and situation. Claudio Gomes discusses the interoperability of simulation units through co-simulation interfaces. Guodong Shao discusses standardization and the pitfalls and potential it offers to digital twins. Finally, Bassam Zarkout discusses the connections of digital twins to AI and data products, and the consequences of such connections for the organization realizing them.

Monitoring Reconfigurable Simulation Scenarios in Co-simulated Digital Twins. Digital twins must track their physical counterpart throughout the whole lifecycle, and as Hansen et al. [9] point out, they must be updated when the structure of the PE changes. In particular, Hansen et al. consider digital twins based on a co-simulation of multiple simulation units, where each simulation unit is a model for a part of the physical system. When the structure of the physical system changes, the simulation scenario (the connections between the simulation units and the master algorithm governing them) must be changed. They propose a monitoring system that verifies at runtime that the new simulation scenario is respected. The authors implement their approach in a language-based approach and evaluate it on an energy system case study.

DiTEC: Digital Twin for Evolutionary Changes in Water Distribution Networks. Degeler et al. [4] discuss a Digital twin for critical infrastructure which is currently being tested in Dutch Oosterbeek region water distribution network. The authors focus on environmental changes, i.e., unexpected changes in the physical behavior or structure that can lead to loss of precision, or expensive operations such as model recalibration. Another focus of the paper is to estimate the state of the network, if not enough sensors are available. To this end, they discuss the use of machine learning techniques, namely neural networks, to act as components of the digital twins that can fill gaps stemming from environmental changes.

Small Scale, Big Impact: Experiences from a Miniature ViL Testbed and Digital Twin Development. Modrakowski et al. [18] present another case study: The use of a digital shadow as part of a vehicle-in-the-loop testbed that is used in reinforcement learning (RL) for automated driving functions. To this end, both the physical vehicle and the simulation model are connected to RL components that learn the functions of their respective counterpart. The paper discusses the used components, with a focus on the available software components and their physical setup of the vehicle.

3 Concluding Remarks

The contributions in this track highlight two current trends in digital twin engineering: the connection to data-driven and ML-based approaches and the challenge to keep the digital entities synchronized with the physical system and react to (possibly unexpected) changes. We look forward to the next years of exciting developments.

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