Proceedings Paper:
Fitzgerald, John, Larsen, Peter Gorm, Margaria, Tiziana et al. (1 more author) (2021) Engineering of Digital Twins for Cyber-Physical Systems. In: Margaria, Tiziana and Steffen, Bernhard, (eds.) Leveraging Applications of Formal Methods, Verification and Validation:Tools and Trends - 9th International Symposium on Leveraging Applications of Formal Methods, ISoLA 2020, Proceedings. 9th International Symposium on Leveraging Applications of Formal Methods, Verification and Validation, ISoLA 2020, 20-30 Oct 2020 Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics). Springer, GRC, pp. 49-53.

https://doi.org/10.1007/978-3-030-83723-5_4

Engineering of Digital Twins for Cyber-Physical Systems

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Abstract. Advances in sensing, communications and data analytics have made it possible to construct virtual replicas of Cyber-Physical Systems (CPSs). Such replicas, known as digital twins, can in principle inform decision making during operation and evolution of the systems they model. This short paper introduces the ISoLA 2020/21 series of papers on the technology and practice of engineering digital twins for CPSs. The focus is on the relationship between model-based design, machine learning, digital twins and CPSs.

1 Introduction

Ensuring the dependability of Cyber-Physical Systems (CPSs) poses challenges for model-based engineering, stemming from the semantic heterogeneity of the models of computational, physical and human processes, and from the range of stakeholders involved. Delivering such dependability may thus be expected to require the coordinated use of multidisciplinary models developed during design alongside models derived from data gathered from the operational system. Together, these have the potential to form the basis of a learning *digital twin*, able to inform decision making both in redesign and in operation.

There is an extensive and diverse literature on digital twins. The Gartner group put the concept among its 10 strategically most important technologies in 2019 because of the many potential benefits by establishing digital twins[5]. The benefits claimed for digital twins include the ability to:

1. reduce time to market,

[5] https://tinyurl.com/y5wkfewe

2. establish preventive maintenance possibilities,
3. enable additional services for the users,
4. visualise the physical twin,
5. enable fault detection and possibly fault diagnosis,
6. increase autonomy, and
7. provide decision support capabilities.

Although there is considerable hype around the potential for digital twins, the technology poses many open research questions, particularly when one considers twins of CPSs and the need for dependability in order that decisions based on twins are sound. The foundations, processes, techniques and tools for engineering digital twins have not so far been the subject of large-scale and systematic study.

- What foundations are needed for a dependable digital twin of a CPS?
- What are the key concepts to be captured in understanding the requirements for a digital twin?
- Where are the limits for a digital twin? When is it 'good enough'?
- What value can be expected from a digital twin, and when it is worthwhile constructing one?

The dependable operation of CPSs requires both the ability to address the consequences of evolving system components, and the ability to explore and identify optimal changes that do not unduly compromise overall dependability. This combination of prediction and response alongside support for informed decision-making and redesign by humans requires both the data derived from operations and the models developed in design. Tackling the challenges of CPS design thus requires a marriage of both descriptive multi-models of the type that might be developed in a design process, and inductive models derived from data acquired during operation. This combination of models, cutting across formalisms as well as across design and operation, has the potential to form a learning digital twin for a CPS, enabling off-line and on-line decision-making.

The goal of the track on the Engineering of Digital twins for CPSs at ISoLA 2020 is to discuss how one can enable the well-founded engineering of digital twins for dependable CPSs. In order to make the benefits listed above a reality there are important challenges to overcome. These range from the creation of a common basis for discourse in what is inherently a multidisciplinary field, through design methodology in the face of the uncertainties that arise when computational process interact with the physical environment, through system architecture to verification. The papers selected for this track address some of these issues from the perspective of formal and model-based approaches, seeking to leverage advances in modelling and verification to address the dependability of digital twins for CPSs.

2 Contributions

In the context of a diverse and rapidly growing literature on digital twins, Yue et al. recognise the need for a conceptual framework to underpin discourse [7]. The framework includes characterisations of digital and physical twins and their environments, and also the critical properties of systems that contain twins, such as notions of fidelity. Central to the benefits claimed for digital twin technology is the ability to manage change, and this in turn requires careful conceptualisation of evolution and life-cycle events in both the digital and physical twins. Further, there is a need to clarify the role of uncertainty in many contemporary CPSs, especially where autonomy is present.

Woodcock et al. [6] consider some of the sources of uncertainty alluded to by Yue et al. In particular, they consider the challenge of handling discrepancies between the values of observed data – which may be subject to noise and delays – and the values predicted in the digital twin. Following an example in agricultural robotics, they consider the description of tolerable deviations the generation of runtime monitors that enforce the identified tolerances. They also consider the use of the digital twin to perform what-if analysis in order to identify optimal system configurations.

Modern CPSs are decentralised, distributed structures. As Kamburjan et al. [2] point out, it may be unrealistic to expect that such CPSs will be captured adequately as physical twins by single models; the architecture of the digital twin will be more heterogeneous and layered. To support such a view, the authors develop a formalised hybrid active object model and demonstrate the expressiveness of the approach. An interesting trade-off is identified between ease of composition and support for simulation: two properties that are needed together to support both analysis and prediction in the digital twin.

Four of the contributed papers examine the potential and the challenges of model-based and formal techniques in realising the potential of digital twins in specific industry sectors: construction, rail transportation, manufacturing and agricultural robotics.

In the construction sector, model-based methods are beginning to bring real benefits, through the use of Building Information Models (BIMs).

In [4], Li et al. examine the potential of 4-dimensional BIM (BIM updated with real-time sensor data from a construction site or building) as a basis for digital twins. In particular, the paper illustrates how abductive reasoning can provide a basis for checking conformance to construction safety codes. The authors note how a consideration of the digital twin from a formal perspective leads to a need for precision in often tangled concepts, such as building code formalisation and building code execution. As with [7], codification of core concepts via an ontology forms a key part of their approach.

Lecomte [3] reviews the classes of model and modelling activity in the rail sector, pointing out that the heterogeneity of models in the industry results from the diverse purposes for which models are constructed (such as specification, validation, and certification) or the diversity of subjects being modelled (such as signalling and rolling stock). Given the characteristics of the sector, Lecomte concludes that a universal model or digital twin is unlikely to arise, but that new analyses (such as performance improvement) or threats (such as that of infrastructure cyber attack) might provide a motivator to develop digital twins in the future.

Matei et al. [5] recount experience in developing a digital twin for a manufacturing system with computational, physical and human elements. A notable feature of this study is the combination of Virtual Reality with machine learning in a manufacturing scenario where a human is collaborating with an assembly workstation (usually a cobot). This includes quite advanced sensors enabling detailed feedback from the human live.

In [1] Foldager et al. have taken the first steps towards exploiting multi-modelling as the basis for a digital twin of an agricultural robot. The paper demonstrates the co-simulation of dynamics using a multi-physics modelling framework that allows modelling of comparatively low-level features such as soil/surface interaction. In such an application, the discrepancies (in time as well as value) between data reaching the twin and the twin's predictions becomes a significant aspect of the twin's design.

3 Concluding Remarks

The contributions in this track make it clear that realising the considerable potential benefits of digital twins for CPSs presents many challenges and opportunities for research and innovation. It is evidently not simply a matter of taking heterogeneous design models and streaming data from a physical twin to identify discrepancies. Many other factors that have a significant impact on the interaction between the physical and digital twins must be taken into account systematically before one can consider the digital twin's predictive functionality to be sufficiently dependable. We look forward to the interdisciplinary research that will be conducted over at least the next decade as digital twin technology comes to deliver its promise in many fully independent domains.

Acknowledgements. We acknowledge the support of the Poul Due Jensen Foundation for research towards the engineering of digital twins; the European Union's funding of HUBCAP (Grant Agreement 872698) and DIGITbrain (Grant Agreement 952071); the Innovation Foundation Denmark for funding MADE FAST; AgroRobottiFleet, ITEA3 for funding the UPSIM project (19006) and Confirm – Smart Manufacturing Ireland (Science Foundation Ireland grant 16/RC/3918).

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