Building a Digital Twin Framework for Dynamic and Robust Distributed Systems

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Abstract. Digital Twins (DTs) serve as the backbone of Industry 4.0, offering virtual representations of actual systems, enabling accurate simulations, analysis, and control. These representations help in predicting system behaviour, facilitating multiple real-time tests, and reducing risks and costs while identifying optimization areas. DTs meld cyber and physical realms, accelerating the design and modelling of sustainable innovations. Despite their potential, the complexity of DTs presents challenges in their industrial application. We sketch here an approach to build an adaptable and trustable framework for building and operating DT systems, which is the basis for the academia-industry project *A Digital Twin Framework for Dynamic and Robust Distributed Systems* (D-RODS). D-RODS aims to address the challenges above, aiming to advance industrial digitalization and targeting areas like system efficiency, incorporating AI and verification techniques with formal support.

Keywords: digital twins, industrial automation, AI, verification and validation, resource utilization

1 Introduction

Industry 4.0 is the digital transformation (a.k.a. digitalization) in the industrial sector that includes automation, data exchange, cloud computing, robotics, Artificial Intelligence (AI), IoT, etc., all used to achieve industrial objectives and intelligent practices through the interaction of people, new technologies, and innovation. Modern industry is facing various complex challenges in adapting to Industry 4.0 contexts, covering the whole lifecycle of products. Further sources of challenges are identified as the inclusion of legacy systems and technologies, finding optimal deployment solutions, and achieving overall performance and robustness of complex systems.

One of the approaches that can provide a unified solution towards digitalization is arguably the exploitation of Digital Twins (DTs) - virtual representations (devices, data, properties, etc.) of actual systems that exist within their environment [4]. DTs use a set of models to describe the system and explore different types of actions on the system. Multiple "real" tests can be run before, during, and after product design. As standards in the DT domain are "barely emerging" [5], "reference architectures" and "DT-platforms"[1] are trying to provide the needed support for companies to cross into the digital world of DT.

The inherent complexity of the DT concept raises additional challenges with respect to industrial utilization [7]. D-RODS addresses problems related to system integration, performance, organization, data volume and quality, and challenges of distributed system automation: integration and compatibility of legacy systems, continuous improvement, lack of skilled labour, etc. D-RODS aims to advance the level of digitalization towards autonomous operations, validated via use cases coming from major Swedish companies in the domains of industrial automation: ABB, transportation: Alstom, and telecommunication: Ericsson.

The overall goal of D-RODS is to propose and validate a reference DT framework based on trustworthy artificial intelligence, supporting highly autonomous system testing and operation, optimal resource utilization and increased resilience to faults. D-RODS aims to support the development and operation of such a framework via modern and complementary approaches.

2 The D-RODS Approach

D-RODS solutions will offer verified and verifiable AI-based approaches, adapted to the size and features of system instances, continuously evolving through the operational stages, improving with respect to their targeted goals. The architecture is organized on several *contexts*, briefly described as follows.

Context: Physical (CP). This layer corresponds to the physical world, containing the plant, the system controlling it, etc.

Context: Learning (CL). This layer (Fig. 1 a)) focuses on the creation of the DT models corresponding to the relevant parts of the other layers. Unsupervised learning, validated by specific V&V methods (transparent, explainable, understandable results), extracts from a long data history a filtered set of data. Based on existing domain expertise and models from libraries, this creates the set of DT models to be employed in the other contexts. Once a complete version of the models is accepted, the **CL** can go offline, to reduce energy consumption.

Context: Functionality (CF) and **Context: Infrastructure (CI).** These similar layers (Fig. 1 b), c)) contain each an AI and a V&V block, which control and enhance the functionality of a complex DT (from **CL**). The DT execution is supervised by a collection of AI algorithms and a V&V procedures. Continuous learning, optimization and behavior evaluation are in place.

Targeted Results. D-RODS proposes a novel architectural set-up uniting DT, AI, and V&V technologies. It targets an increase in the trustfulness of AI approaches via formal analysis and online testing, optimizes operations, resource usage and power consumption, and improves maintainability aspects. The D-RODS framework will cater to the accuracy and efficiency of employed models by continuous learning and verification, towards high levels of autonomy. The

[1] e.g. DIGITBrain. https://digitbrain.eu/

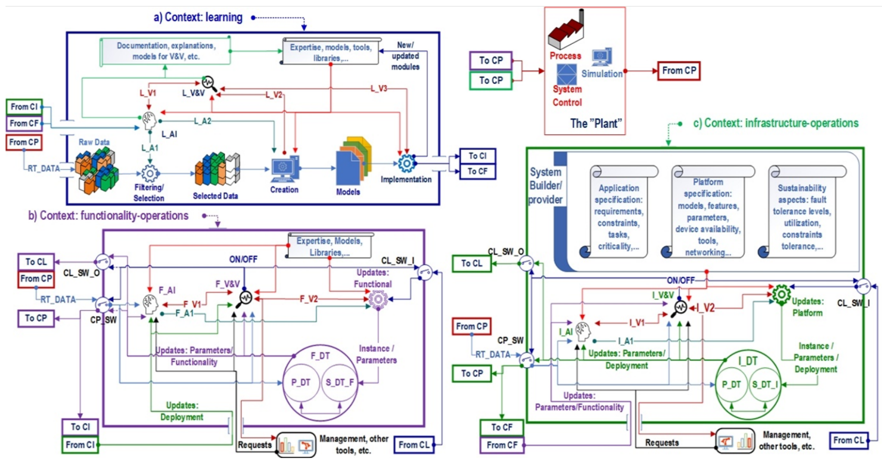

Fig. 1. Approach details.

cross-domain validation is expected to innovate the content of "reference architectures" in the context of DT developments.

D-RODS also proposes, verifies and demonstrates a novel methodology to detect system faults and means to mitigate their impact, based on: a) new AI-based approaches to identify HW failures; b) a new and verified learning solution to acquire adaptation strategies to re-distribute resources in reaction to identified faults. This provides a novel dimension in the DT research, toward enhancing the resilience and robustness of digitalized systems.

Focusing on AI methods, D-RODS is set to refine system performance prediction and resource utilization optimization. For V&V, D-RODS is deriving from past work on passive testing, integrating formal verification and runtime testing. It ensures that the developed models, when incorporated into DT, are accurate and continuously monitor operational correctness. Techniques will include design verification, continuous monitoring, and metamorphic testing.

Related Work. In manufacturing and automation, several studies (e.g., [1]) show the usefulness of AI in monitoring, maintenance, error diagnosis and real-time optimization tools, at elevated costs in energy, though. If concepts such as DT and automated model creation exist, consumption may be reduced up to 20%, pending on computation efficiency and accuracy of models [6].

In the telecom, the non-incremental leap from 4G to 5G came with large implementation challenges. Existing assurance processes become inadequate, requiring new techniques and related procedures. Device and network DTs, using of AI and the correctness of results are critical for the industry as a whole [2].

Work on formal verification of AI components has been carried out, especially for neural networks [3]. The system-level simulation-based formal analysis of AI-based systems, performed by the VerifAI toolchain [8] is complementary. It comes close to D-RODS' envisioned verification approach, yet it does not apply game-theoretic model checking for AI verification, and it does not target distributed learning in networked environments, which we tackle in D-RODS.

AI and big data have played an important role in the development and training of production control optimization of DT models for industrial applications [9]. However, AI-related techniques have been only used for planning, scheduling and control of the operation of machines. They have not been exploited for monitoring and managing the sensing-computing system of DTs for enhancing their resilience, robustness and energy efficiency.

3 Conclusions

We introduced the D-RODS approach as a novel framework for the implementation of DT within Industry 4.0 paradigms. It is formulated to address existing challenges by creating a cohesive integration between AI methodologies, V&V techniques, and current DT concepts. This should foster enhanced system efficiency, reduced power consumption, and prolonged system component life. The inclusion of AI in D-RODS not only facilitates better simulation and prediction models but also offers advanced fault detection and mitigation mechanisms.

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