



Cyber-Physical Systems and Digital Twins in the Industrial Internet of Things

Christos Koulamas and Athanasios Kalogeras,

Industrial Systems Institute/ATHENA

A digital twin is a virtual representation that serves as the real-time digital counterpart of a physical object or process and addresses every instance for its total life cycle.

Operational models and other virtual representations of cyber-physical systems (CPSs) are a common industrial engineering practice today. The evolution of Internet of Things (IoT) and AI technologies enables complex interactions of such virtual representations for the total lifetime of system instances under the digital twin (DT) concept, which poses a number of challenges for its seamless integration in the modern industrial environment.

Digital Object Identifier 10.1109/MC.2018.2876181
Date of publication: 15 January 2019

CPSs lie at the cross section of the physical and digital worlds. Integrating physical processes and computer systems is the main challenge presented by them, as the computational cyber part continuously senses the state of the physical system and applies decisions and actions for its control. CPSs present a wide range of applications in different sectors, including manufacturing, energy,

health care, consumer services, and monitoring of critical infrastructures.

CPSs are mostly networked systems characterized by distribution of functions and often wireless connectivity between intelligent physical devices, providing sensing and actuating as well as control capabilities. Real-time behavior is a critical challenge, as the continuous monitoring and control of the physical world has to be ascertained. They represent complex, flexible, and adaptive systems, whose constituent elements are characterized by increased autonomy and intelligence. Cybersecurity mechanisms need to be integrated in a holistic approach

toward detection of attacks, resilience, and privacy concerns.

The Industrial IoT (IIoT) is an enabling technology of CPSs, providing the networking infrastructure for physical objects to sense, communicate, and interact. The spread of the IIoT has led to an explosion of data and information. With 21 billion connected things by 2020,¹ the IIoT market is estimated to add \$14.2 trillion to the global economy by 2030.² Manufacturing, connected logistics and transportation, and energy and utilities represent the three largest markets for the IIoT. Digitization of these markets creates a plethora of data and new opportunities for companies to extract knowledge out of these data.

THE DT CONCEPT

The increasing availability and ubiquity of real-time operational data, as well as the boost of AI implementation capabilities in learning and reasoning, represent drivers toward realizing a vision of physical products or processes having accompanying virtual representations that evolve throughout their entire life cycle. Such virtual representations, or DTs, represent real-time digital counterparts of physical objects. There is not any unique, globally accepted, and common closed definition of the DT concept; however, there are certain aspects on which most existing definitions agree.⁷ A DT is virtual (that is, digital), it includes both static (that is, design documents, process specifications, and so forth) and dynamic (that is, data acquisition and simulation) parts, and it addresses every instance of its twin product or process for its total life cycle.

Could DT be a new marketing buzzword for a concept that already exists? There might be some truth in this: a part of the DTs' expected capabilities (for example, precise simulation of the physical thing's behavior) could already be utilized in current engineering practices.

Still, the DT concept attempts to materialize a bidirectional integration of the digital and physical worlds, interconnecting physical things with their digital counterparts while also bringing to the physical world changes to its DT.

Gartner included DT as top strategic technology trend number four for 2018 (among the top 10 trends that will contribute to the intelligent digital mesh, that is, the integration of things, services, content, and people).

One direct utilization of a DT is in the field of asset management. Being the cyber twin of a physical thing and having access to real-time information regarding the physical thing as well as to related historical data, the DT can help optimize physical asset performance through efficient predictive and preventive maintenance operations, thus reducing overall maintenance costs and downtime.

Furthermore, the DT can simulate the behavior of the physical thing that it is twinned with—or of an associated process—and can thus contribute significantly to performance optimization. It can act as a tool for predictive analysis, predicting the performance of the physical thing or its associated process. If this example is enlarged in the scope of a digital enterprise, then the overall process, production system, or product may be optimized. Potential benefits include, among others, optimizing production scheduling, identifying potential bottlenecks, assessing asset utilization, and minimizing production lead times.

The DT offers a total life cycle approach with reference to its physical twin, either a thing or a process. Product design, new product launch, manufacturing process setup, and integrated supply chain management are facilitated. It is essential, though, to point out the principal difference of the virtual representation of a DT compared with well-known and widely used

relevant modeling engineering in design, simulation, and testing: the permanent connection between the real and the virtual part for the total life cycle of a specific system instance. This connection means that information exchange between the system instance and its DT counterpart (that is, sensing and often also actuating infrastructure) can be part of a cyber-physical system on its own, depending on the type of information exchange—whether a real-time data flow or some systematic data collection that is integrated offline in the behavior of the DT.

INTEGRATION CHALLENGES

The need for a bidirectional life cycle-extended integration between the physical world and its DT mandates a relevant supporting reference architecture. Different initiatives deal with the IIoT providing relevant reference architectures, the most important of which are Industry 4.0, the Industrial Internet Consortium (IIC), and Society 5.0.

The Reference Architecture Model for Industry 4.0 (RAMI 4.0) is a three-dimensional model along three axes (hierarchy, architecture, and product life cycle), with IT security and data privacy as enablers (see the right side of Figure 1).³ The Industrial Internet Reference Architecture (IIRA) of the IIC⁴ comprises four different viewpoints: business, usage, functional, and implementation. The functional viewpoint (see the left side of Figure 1) is, in turn, divided into five domains (control, operations, information, application, and business), four cross-cutting functions (connectivity, distributed data management, analytics, and intelligent and resilient control), and six system characteristics (safety, security, resilience, reliability, privacy, and scalability). The implementation viewpoint utilizes a three-tier implementation architecture comprising the enterprise, platform, and edge tiers (see the lower part

of Figure 1). A mapping between RAMI 4.0 and IIRA is also possible.⁵ Finally, Society 5.0 represents the related Japanese initiative driving toward a new hyper-smart society and extending to different application domains. Its enabling technologies comprise the Internet of Things, big data, ambient intelligence, and robotics.⁶

The interweaving of the DT with its physical counterpart starts with the capture of data generated by sensing things in the manufacturing environment. This provides the DT with real-time data of the physical world it is twinned with. This step can be mapped to the asset layer of the architecture axis of RAMI 4.0. These data are then aggregated and combined with historical data pertaining to the manufacturing process as well as relevant data at the enterprise level. This step drives from the physical to the cyber part and corresponds to the integration layer of RAMI 4.0.

Then, at the communication layer, data move to the fog, the edge, or the cloud depending on the architecture that is followed. Data analytics are applied to these data, and useful information is derived. This information can

guide some optimization in the product or process. Some action is triggered in the real world by the DT to achieve this.

Furthermore, as the cyber and physical perspectives of the DT may already blur the borders between the DT of a complex cyber-physical system and the system itself, embedded technology evolution has already started to challenge typical architectural patterns in the realization of DTs, which usually call for relatively heavy centralized computing power and relevant data center and cloud infrastructures. There are applications that have inherent characteristics and requirements that provide a natural fit to highly distributed intelligence at the edge. However, the benefits of similar setups, mainly network bandwidth and cloud processing cost reductions but also responsiveness, dependability, scalability, and security improvements, can be exploited in a wider set of domains, especially in fault detection and diagnosis for preventive and predictive maintenance.

There is ongoing research on enabling AI capabilities in embedded devices,^{8,9} while specialized hardware and real-time embedded analytics

frameworks are already in the market, justifying their necessity in various industrial settings.¹⁰ This is expected to lead to a wider adoption of this specific architectural paradigm, considering the high achievable degree of containment for a relatively small “twin” of a tiny but critical “thing,” which is able to create, train, consult, and adapt its DT onboard and in real time without any interaction with the cloud. Such twins can be then envisaged as capable of being combined in a system-of-systems fashion to create larger distributed models for DTs of highly complex cyber-physical systems.

The DT concept in the IIoT context generates a number of challenges. Its constituent elements are quite diverse. Product and production process models must be seamlessly integrated with simulation and prediction models, as well as with tools and systems dealing with data analytics and optimization; nontypical, embedded, and mobile computing platforms must also be considered. This interoperability challenge of combining completely different models, systems, and tools represents an area in need of significant research. Mapping and integration of the DT and its

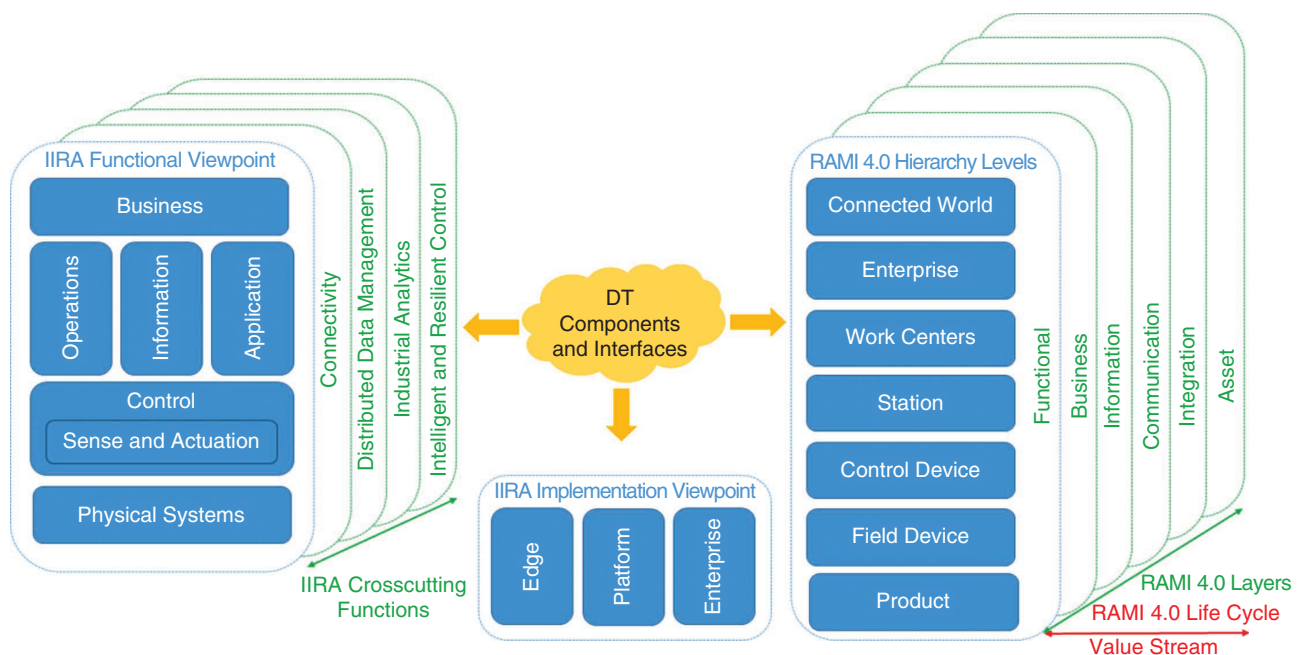


FIGURE 1. The CPSs and digital twins (DTs) in the Industrial IoT.

functionalities on the prevalent reference architectures for the IIoT is also a necessity (see Figure 1).

The DT is still mostly at a conceptual stage, in terms of demonstrating wide industrial adoption and becoming a well-defined engineering practice within the industry. There is a need for research dealing with the previously listed challenges. Further, there is a need for a unified framework to build, out of the corresponding physical world model, its DT. This framework should offer the full range of tools necessary for DT operation. 

REFERENCES

1. M. Hung. (2017). Leading the IoT. Gartner insights on how to lead in a connected world. *Gartner*. [Online]. Available: https://www.gartner.com/imagesrv/books/iot/iotEbook_digital.pdf
2. Accenture. (2015). Winning with the industrial Internet of things. *Accenture*. [Online]. Available: https://www.accenture.com/t20160909T042713Z_w_us-en/_acnmedia/Accenture/Conversion-Assets/DotCom/Documents/Global/PDF/Dualpub_11/Accenture-Industrial-Internet-of-Things-Positioning-Paper-Report-2015.pdf
3. P. Adolfs, S. Berlik, W. Dorst, J. Friedrich, C. Gericke, M. Hankel, R. Heidel, M. Hoffmeister, C. Mosch, R. Pichler, U. Rauschecker, T. Schulz, K. Schweichhart, E. J. Steffens, M. Taube, I. Weber, M. Wollschlaeger, and S. Mätzler, "Reference Architecture Model Industrie 4.0 (RAMI4.0)," Deutsche Institut für Normung e.V. (DIN), Berlin, Germany, DIN SPEC 91345, 2016.
4. S.-W. Lin, B. Miller, J. Durand, G. Bleakley, A. Chigani, R. Martin, B. Murphy, and M. Crawford. (2017). The industrial Internet of things, volume G1: Reference architecture. *Industrial Internet Consortium*. [Online]. Available: https://www.iiconsortium.org/IIC_PUB_G1_V1.80_2017-01-31.pdf
5. S.-W. Lin, B. Murphy, E. Clauer, U. Loewen, R. Neubert, G. Bachmann, M. Pai, and M. Hankel. (2017). Architecture alignment and interoperability Industrial Internet Consortium and Platform Industrie 4.0 Joint Whitepaper. *Industrial Internet Consortium*, Needham, MA. [Online]. Available: https://www.iiconsortium.org/pdf/JTG2_Whitepaper_final_20171205.pdf
6. Japanese Cabinet Office, "Society 5.0," *Japanese Cabinet Office*. Accessed on: Nov. 19, 2018. [Online]. Available: http://www8.cao.go.jp/cstp/english/society5_0/index.html
7. I. Negri, L. Fumagalli, and M. Macchi, "A review of the roles of digital twin in CPS-based production systems," *Procedia Manufacturing*, vol. 11, pp. 939–948, Sept. 2017.
8. N. D. Lane and P. Warden, "The deep (learning) transformation of mobile and embedded computing," *IEEE Computer*, vol. 51, no. 5, pp. 13–16, May 2018.
9. J. Tang, D. Sun, S. Liu, and J.-L. Gaudiot, "Enabling deep learning on IoT devices," *IEEE Computer*, vol. 50, no. 10, pp. 92–96, Oct. 2017.
10. C. Middleton. (2018) Digital twin AIs designed to learn at the edge. *Control Engineering*. [Online]. Available: <https://www.controleng.com/single-article/digital-twin-ais-designed-to-learn-at-the-edge>

Call for Articles



IEEE Software seeks practical, readable articles that will appeal to experts and nonexperts alike. The magazine aims to deliver reliable information to software developers and managers to help them stay on top of rapid technology change. Submissions must be original and no more than 4,700 words, including 250 words for each table and figure.

**IEEE
Software**

Author guidelines:
www.computer.org/software/author
Further details: software@computer.org
www.computer.org/software

CHRISTOS KOULAMAS is a research director at the Industrial Systems Institute/ATHENA Research Center. He is a Senior Member of IEEE. Contact him at koulamas@isi.gr.

ATHANASIOS KALOGERAS is a research director at the Industrial Systems Institute/ATHENA Research Center. He is a Senior Member of IEEE. Contact him at kalogeras@isi.gr.