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Chapter 7
Fluidware Meets Digital Twins

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Abstract The rapid progress in digital technologies has opened up opportunities for creating and using digital twins, which facilitate and advance the connection between physical systems and their virtual counterparts. In this chapter we report an overview on the topic of digital twins which is gaining importance especially in the design and implementation of complex IoT and Cyber-Physical systems. In particular, we describe the contributions of the Fluidware project that relate to digital twins and discuss remaining challenges and emerging concepts that enhance the one of digital twin.

Key words: Fluidware, Digital Twin, Internet of Things

7.1 Introduction

A rapid rise of interest in the potential of Digital Twins (DTs) to transform a vast range of Internet of Things (IoT) and Cyber-Physical System (CPS) applications [36] has recently emerged.

A DT is a virtual representation of a physical object, process, or system. It uses real-time data and simulations to mimic the behavior, characteristics, and interactions of its real-world counterpart [29, 29]. The concept of a DT allows organizations to

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gain insights into the performance, maintenance, and optimization of physical assets and processes. It brings together various technologies, such as the Internet of Things (IoT), data analytics, artificial intelligence (AI), and cloud computing, to create a comprehensive and dynamic representation of the physical entity in the digital realm. The rapid advancements in the mentioned digital technologies have paved the way for the development and utilization of DTs that allow bridging the gap between physical systems and their virtual representations.

In particular, the Internet of Things is seen as the key enabler to filling the gap between the physical and virtual worlds, and it has been defined as the backbone for the development and use of digital twins [32]. The value that DTs add to the management, development and commercialization of IoT systems can have a disruptive impact in the whole ICT landscape of the next few years, further bridging the physical-virtual divide. The 2023 Gartner emerging tech impact radar, places DTs among the most impactful emerging technologies and trends [60].

The idea of twinning physical assets is over 50 years old but the true rise of DTs corresponded with the IoT. Indeed, simultaneously, on the one hand the plethora of IoT solutions has enabled main DT functionalities, solving those technological and infrastructural issues that have limited DTs spread so far; on the other hand, the wide sea of heterogeneous IoT devices, data and services requires adequate abstraction, encapsulation, prototyping, management and commercialization solutions that can be successfully pivoted on the DT concept. In fact, implementing DT solutions is not a trivial task. Industry pioneers and researchers interpreted the DT concept during the last years, each reporting and emphasising different characteristics [5, 56]. As a result, no recognised standard definition and no unified solution to design and implement all the characteristics and functionalities of a DT is available [3, 25]. Within the scope of the Fluidware project [17] [18], conceptual and practical solutions for the integration between DT and IoT have been explored as well as the state-of-the-art of main DT-aided IoT Platforms reviewed [24, 25].

In this chapter we first provide, in Section 7.2 an overview of the Digital Twin concept, of its characteristics, its enabling technologies and application scenarios. We then report, in Section 7.3 the contributions resulting from the Fluidware project that can be adopted in the process of developing Digital Twins solutions. In Section 9.4 we report a discussion on Digital Twins and the challenges that they face. Section 9.6 concludes the paper with a short summary, envisioned implications, and future work.

7.2 Digital Twins Overview

In this section, we provide an overview on the characteristics of DTs, their enabling technologies and the various application domains that can benefit from their adoption.

7.2.1 Digital Twin Characteristics

DTs are considered as digital models that represent and have a direct connection with real entities (e.g., through IoT sensors and actuators). Data collected directly from the physical entities allow to update their digital representations. From such digital representations, information can be extracted that may impact decision-making and guide changes to be reflected in the real environment. Simulation techniques and AI adoption enable to predict failures, to optimise the system, to design novel features, to ease and accelerate decision making, and to improve productivity. A DT can persist for the whole entity's life-cycle, from design to implementation, deployment, maintenance and disposal [30].

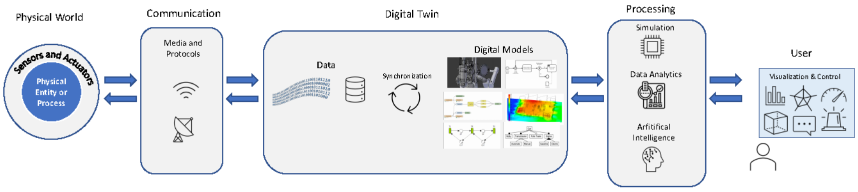

Fig. 7.1: Digital Twin Concept Overview

DTs can be used to reflect the appearance of a real entity, through the design and use of *graphical representations* such as 2D/3D models. Some models that characterize DTs, are used to represent *states* in which a physical entity can be (e.g., turned on, turned off, active, idle, or error state), *behaviors* the physical entity can have, and the *context* in which the physical entity acts. This models are updated through data captured from the physical entity and environment, in such a way to properly monitor it and to reason about the actions the status of the physical entity and the activity it is performing so to plan further operations. A physical entity can be composed of smaller components (e.g., machinery can have several mechanical parts), if necessary, each single component could have a respective digital representation and DT, leading to a *composition* of DTs.

As a DT is a digital representation of a physical entity, it is fundamental that a connection between the physical and the virtual replica exists so that the DT can receive and send data from/to the physical entity. This *interaction* is necessary to maintain a synchronization *between* the *physical and virtual entities* in such a way as to reflect changes from the virtual world to the physical one and vice versa. This process is often referred to as *twinning process* [5]. For example, an event occurring in the physical world will require updating the virtual replica to reflect changes to the digital entity, vice versa when an action is requested to a DT, a command could be sent to the physical counterpart so that it also performs that action. DTs can *exchange data with information systems* to collaborate and provide more elaborated services. This way, a DT can send and receive data from/to external sources or services. The possibility for DTs to *interact between each other* and to exchange data is seen as an important characteristic necessary for establishing networks or communities of DTs. In this way, DTs can exchange information and modify their behavior according to the context they perceive.

DTs, can process and analyse both historical and real-time data to understand the occurred events and the current status the real entity is in. DTs can rely on data analysis techniques to estimate when a certain situation will occur, e.g., when maintenance should be performed. DTs, as recognised by all the analysed literature, are used to conduct *simulations* of the activities the real entity can perform, or of the data it can process and the state it can reach. This allows to analyse case scenarios that the real entity can be subject to and gather useful insights, such as possible changes to perform on the real entity to optimize it and achieve better performance. DTs can also be designed to autonomously reason about their status and perform possible automatic adjustments that the physical counterpart could not do by itself.

7.2.2 Enabling Technologies

Digital Twin is certainly one of the paradigms (e.g., software agents, model-based engineering, grid computing) which has discovered newfound lifeblood and application fields with the emergence of IoT [11, 26, 27]. IoT data, technology and protocols have thus empowered the DTs and fostered their evolution with the contribution of other relevant paradigms like AI, big data, etc. Indeed, the most advanced examples of DTs, also called Cognitive Twins or Intelligent DTs, are defined just in the context of IoT Platforms and leveraging on their connectivity, analytics, simulation and visualization tools. Conversely, the value DTs can bring to the IoT is also relevant, with notable impacts on the design, prototyping and commercialization of current and future IoT devices and services. These aspects are key since they typically hinder developers and organizations in fully achieving the IoT vision despite its inherent heterogeneity, large scale and complexity.

In August 2020, within the context of the Object Management Group, the Digital Twin Consortium has started working on a taxonomy and on standards for DT enabling technologies, including the IoT. In particular, IoT-related technologies like EPC and RFiD can greatly support *DT identification*; ontologies coming from the IoT realm, like SensorML, SSN and OWL, can ease also the *DT modeling*; XML, SOAP, JSON, Flatbuffers, have recently found success also for the *DT serialization* for the versatility and efficiency shown as IoT data interchange formats and management mechanisms; the plethora of network/message protocols paved by IoT (foremost LoRaWAN, Bluetooth, 802.11.*, ZigBee, MQTT, CoAP) can be exploited to support *DT connectivity* according to the specific requirements in terms of bandwidth and energy consumption, latency, overhead, coverage, data rate, wired-wireless transmission etc; if provided with IoT API (e.g., OGC SensorThings and Webinos IoT), DTs can access sensors and actuators in a transparent and secure way, thus achieving truly *Cyber-physicality*; finally, microservices and containers are possible candidates for programmatically supporting the integration and composition of several IoT devices but also of DTs, automating their *deployment* and simplifying the design of their complex services.

These IoT-enabled DT functionalities are concretely implemented within the IoT Platforms software instruments generally used to organise and handle: IoT devices and their interactions; the data they capture from the environment; the manipulation, the processing, the visualisation of such data; and the interaction with external service [17]. These fully support stakeholders in the scalable, efficient and secure management (i.e., connection, access, protection, analysis, visualization) of heterogeneous (IoT, but not exclusively) data and devices, aiming to streamline development processes and provide greater value to business. To this end, an increasing number of IoT Platforms has started offering support for the creation, integration and exploitation of DTs along their entire life (from the initial DT model tuning to the periodic synchronization given by the entanglement with the physical assets), leveraging on the rich data, analytics tools and connectivity mechanism provided by the IoT Platform itself [47, 33] making them become suitable options for implementing DT solutions [52, 4, 8].

The landscape of IoT platforms is wider every day so, in the following, we briefly introduce ten of the most relevant ones provided both by cloud and industrial vendors: (i) Amazon Web Services (AWS); (ii) Azure Digital Twin; (iii) Bosch IoT Suite; (iv) Google Cloud IoT Core; (v) Lumanda; (vi) Predix; (vii) MindSphere; (viii) SAP Cloud Platform; (ix) ThingWorx ; and (x) Watson IoT Platform. In [25] a comparison of DT characteristics and IoT Platform functionalities is reported.

7.2.3 Digital Twin Application Scenarios

The DT paradigm is adopted nowadays in multiple application scenarios, ranging from Industry 4.0 [61], there including and especially manufacturing, to healthcare [40], and smart cities [57], there including smart mobility and intelligent transportation [51]. In the following we report two example: one from the healthcare sector and the other focused on cooperative driving.

In healthcare, major trauma management, is one of the challenging scenarios where DT-based solutions have been already conceived. There, physicians must have strong heterogeneous expertise, promptly identify a diagnosis, and quickly provide medical aid. In [22], a DT based solution is outlined, conceptually structured in three stages:

1. Management of the emergency calls. For the trauma event a new DT is created, and linked to the DTs of both the available ambulance and the designated rescuer.
2. Pre-hospital management. DTs of patients are created and linked to the event DT, as well as to the trauma centre DT in charge of patient intake.
3. In-hospital management. The trauma event DT keeps tracking everything that happens to the patient, and gets linked to the DTs of the team of physicians involved in trauma management, and to the hospital rooms needed.

All these DTs and especially their semantic interlink are used to support various kinds of agent-based applications, e.g. a personal assistant agent for the medical personnel, and a trauma tracking applications for documentation purposes.

DTs can have a major role in supporting cooperative driving with both autonomous and non-autonomous vehicles sharing the road infrastructure There, basic services such as intersection crossing, parking, and ride-sharing will need to be redesigned [44]. A WoDT can play the role of the enabling coordination infrastructure in the case of intersection crossing by following three major steps.

1. The municipality deploys the intelligent road infrastructure on a target intersection. Relevant Road Side Units (RSUs) are deployed, such as smart cameras to monitor traffic conditions. The DT of the intersection and of the crossing process are created;
2. As soon as vehicles approach the intersection, their DTs are linked to the intersection and to the crossing process, and the coordination process to establish who gets the right of way.
3. Depending on the specific intersection crossing policy [44], the crossing process DT assigns the right of way or a waiting command to the vehicles' DTs, until all vehicles are served.

The whole crossing process is highly dynamic: links amongst DTs are created whenever vehicles approach and leave the intersection, and DTs are used to continuously reflect (and control, wherever possible) the state of the involved assets, such as vehicles themselves, RSUs, as well as the (coordinated) crossing process.

For further scenarios, the interested readers can refer to surveys available in the literature [48].

7.3 Fluidware for Digital Twins

The Fluidware project led to several contribution that can be adopted to design and develop DT applications.

7.3.1 Designing Digital Twin Solutions

Fluidware also contributed with the development of MDE approaches combined with Low Code development for supporting the design and implementation of IoT application [15, 17, 18, 20]. Such approaches support the design of IoT applications by means of graphical notations that abstract from the specificity of a single scenario. They allow handling the high variability of the IoT domain, and enable the reuse of knowledge in the production of different solutions for IoT applications. Such successful approaches can also be applied in the design and development of DT solutions. A first contribution towards this direction involves the proposal of a graphical notation

(DTMN - Digital Twin Modelling Notation) and software instruments that have been defined for supporting the design and conceptualization of DT solutions [25, 20]. A meta-model has been designed to incorporate the main characteristics of DTs, derived from a literature study, therefore the defined graphical notations allows to reason in terms of the physical *entity* or *system* that need to be digitally represented; the *state* in which an entity can be and the transitions that can cause state changes; the *visualization* of data and of the digital representation of the entity; *context* in which the physical twin is located; *data* that can be handled; and *application* that can be defined.

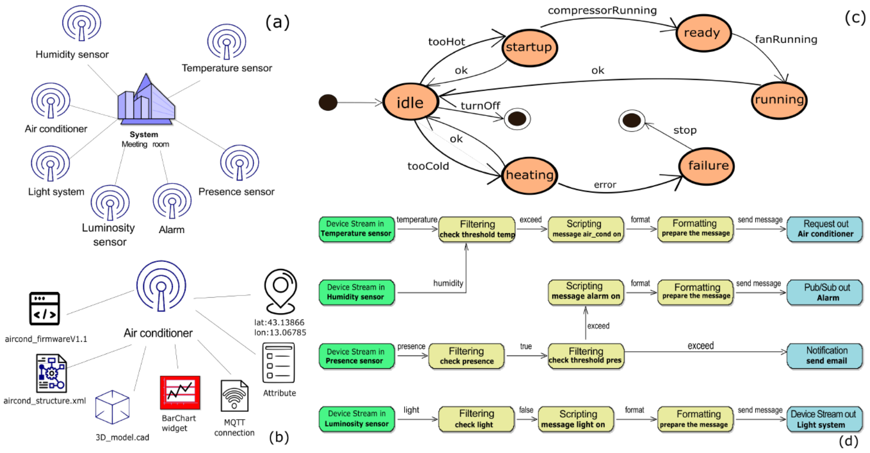

Fig. 7.2: Models representing (a) all the entities involved in a meeting room system, (b) a detailed visualisation of an air conditioner digital twin, (c) the air conditioner state machine, and (d) the entire meeting room system application logic [25].

The usage of DTMN to design a DT solution for a sample scenario regarding a smart meeting room is reported in Figure 7.3. Figure 2(a) illustrates the Context viewpoint. It represents a meeting room model along with the various entities involved. System and entity names, as well as descriptions, can be ascribed. Further specialized data relevant to each entity can also be integrated. Figure 2(b), provides details about a specific Entity, in this case an Air conditioner. This entity could be intricately elaborated with supplementary components that align with the attributes of a DT, encompassing features like its composition, traits, spatial placement, connectivity, and associated descriptive files. Figure 2(c) reports the Air conditioner's state machine perspective. Each DT can be outfitted with a state machine configuration, delineating the distinct states it can assume and the transitions that precipitate state alterations. Figure 2(d) reports the portion of the notation used to describe data manipulation activities and the overall application logic of a DT solution. It can be seen as a way to describe the management and control of the intelligent meeting room including: temperature and humidity-based air conditioner regulation, dispatching notifications to the manager via email, triggering an alert in situations of room overcrowding, and the automatic management of lighting, driven by luminosity sensors.

In **Book Chapter A BPMN Driven Approach for the Management of IoT Processes** we presented an MDE approach that starting from a domain-agnostic and standard notation called BPMN - Business Process Model and Notation [49] - allows describing collaborations between IoT processes carried on by multiple devices up to their execution made possible by so called BPMN engines [14]. Similarly to what we presented there, the DTMN modelling notation could lead to the definition of Model-Driven Engineering (MDE) approaches that can be used to go from models designed with DTMN to actual executable code. Given the strong relation between DT and IoT concepts, DT solutions are being developed through IoT platforms that have been extended to represent DT aspects [24, 52]. Such DT-ready platforms can be the target of MDE approaches, and code derived from models can be executed on such platforms. Especially, given the variety of IoT and DT platforms that are available in the market, the use of a cross-platform approach that allows the design of a DT solution once and the deployment on multiple target platforms, like proposed in [20], can be envisaged as a possible direction. This approach would allow DT solution designers to select multiple target platforms based on their specific support for each DT characteristic.

7.3.2 Agentified Digital Twins

Within the scope of the Fluidware project, efforts to take the lessons learned from the World Wide Web, the IoT, multi-agent systems, and distributed systems, have also been conducted and this led to to the definition of an event-driven, decentralised, interoperable, linkable and discoverable vision of DTs named Web of Digital Twins (WoDT) [22, 46]. The WoDT can be actually shaped into specific application domains with peculiar challenges and constraints related, for example, to the enrolment of heterogeneous physical assets, a structured hierarchical organisation, and dynamic evolution in terms of interactions and knowledge representation. On the one hand, the WoDT allows to model DT's properties, behaviours, and relationships, and consequently to represent large-scale and complex physical environments as an open ecosystem of connected and interoperable DTs.

Also the potential synergies between agents and DTs, and Multi Agent Systems (MAS) and (networks of) DTs, to reason about both the individual and collective (system) level have been investigated. The proposed model, reported in Fig. 7.4 and the abstract architecture define a basic conceptual framework, that can be mapped onto a variety of concrete deployment scenarios and implementation technologies, with the aim to be a unifying horizontal layer on top of the physical assets. DTs are seen as entities interlinked in a web of semantic, dynamic relationships, that enable structuring a dynamic application domain.

The proposed WoDT vision supports the definition of a new cyber layer where applications, agents, and services can implement and orchestrate new smart and

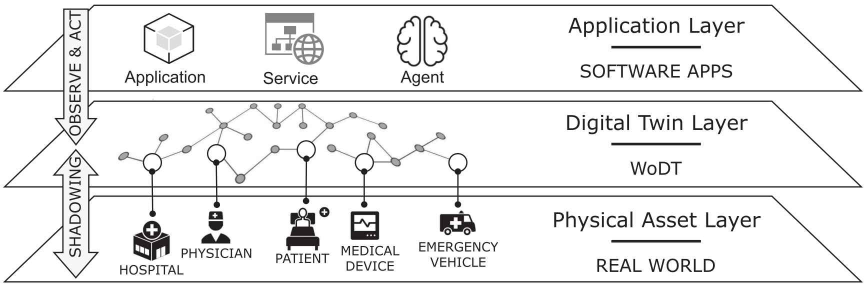

Fig. 7.3: WoDT layered view [22].

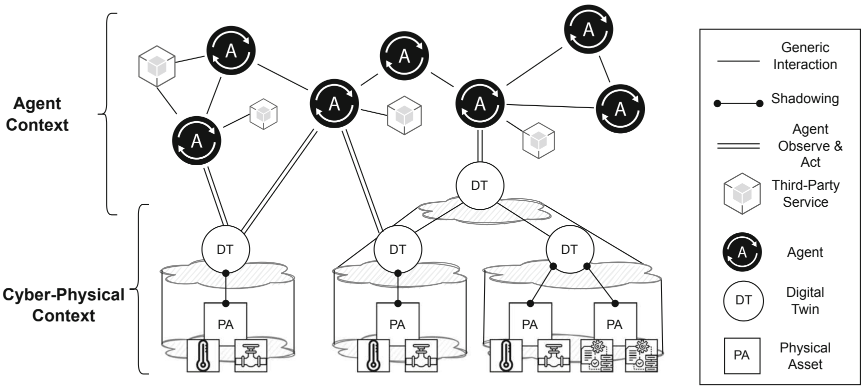

Fig. 7.4: Agent and Digital Twins relation [46].

dynamic systems of components by relying on a structured and integrated DT's overlay, without the responsibility to handle the fragmentation and the heterogeneity characterising the physical layer. Moving forward from the local scope of a single application domain, the possibility to exploit a uniform and interoperable Web of DTs also opens the way to the design of a new generation of cross-domain computational infrastructures, trying to mirror the physical world where existing assets seamlessly move and interact across multiple contexts at the same time. For example, a person can be an employee for a company and a patient for the health system, or an ambulance can be a vehicle on the street and a resource for the trauma management ecosystem. Through the adoption of WoDT, DTs from multiple realms can start cooperating (potentially on demand) to reach a shared goal or to opportunistically implement a new behaviour, that is something quite difficult to achieve in the siloed environments representing the state of the art.

7.3.3 Collective and Augmented Digital Twins

The engineering of self-organising cyber-physical systems can benefit from DTs, virtual devices, and (augmented) collective DTs. In particular, collective DTs provide for a design construct towards collective computing, which can be augmented with virtual devices to improve the performance of existing self-organising applications—as shown through swarm exploration and navigation scenarios [13].

Especially, the *collective computing* [30], or the *artificial collective intelligence* paradigm [31], can contribute to and integrate with the DT approach in two main ways [13]. First, a digital thread providing the bidirectional synchronisation between a DT and the corresponding physical twin may be *supported by a collective process*, whereby multiple devices collaborate in order to provide an effective representation or reification of the target state. Secondly, considering collectives as first-class citizens in the design of socio-technical or multi-agent systems suggests the possibility of *considering DTs for entire collectives* (e.g., the DT for a whole swarm of robots).

Collective computing techniques can be adopted to support the fidelity or the implementation of digital twins (DTs). For instance, the shape information about a physical entity may be supported in a DT by multiple cameras [34]. As another example, the mean temperature of a digitalised room may be computed by combining the contributions of multiple thermometers. Related *sensor fusion* techniques have been applied to DTs e.g. in the smart vehicle domain [34].

A *Collective Digital Twin (CDT)* is a DT that has a collective nature, namely one that is associated to an entire collective [14]. Consider the DT of an entire *swarm* of robots: it can model swarm-level information that goes beyond the properties and state of an individual robot—e.g., macroscopic properties like the direction in which the swarm as a whole is moving, or results of consensus. A CDT may be implemented or represented as a collective of collaborating DTs (see Figure 7.5). The definition of a CDT is a matter of reification, and is motivated by the need of capturing macroscopic information as well as providing an abstracted monitoring and control interface over ensembles of physical entities.

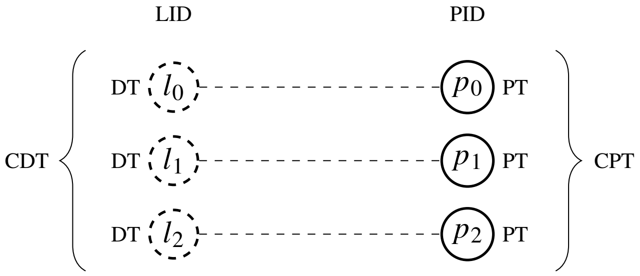

Fig. 7.5: Collectives of digital (CDT) and physical twins (CPT) [13].

The CDT notion can be *augmented* considering virtual devices that have no physical counterparts [14, 13]. This leads to a notion of *Augmented CDT* (see Figure 7.6), which provides the software model of an augmented reality system and enables activities like the steering of self-organising behaviours [33, 32]. In [14, 13], for instance, virtual devices are spawned to increase the coverage of a spatial area in order to improve crowd-aware navigation and exploration processes. To implement this, two main problems have to be addressed: the creation of virtual devices (*synthesis*), and their integration in the CDT (*augmentation*). The overhead associated to the augmentation should be motivated in terms of new or improved functionality.

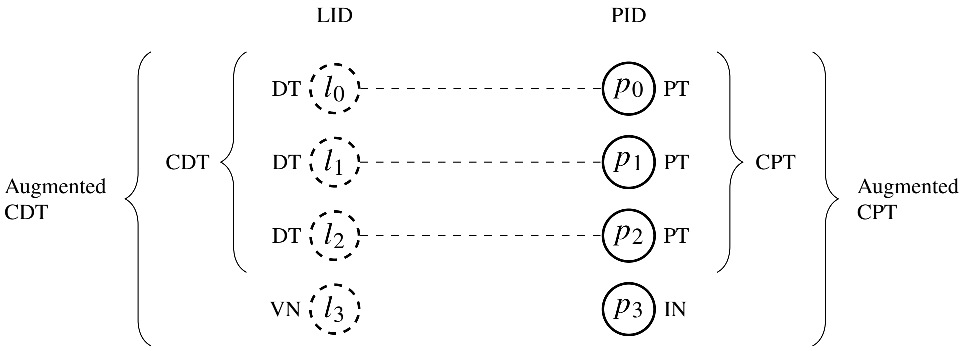

Fig. 7.6: Augmented collectives of digital and physical twins [13].

7.3.4 Fluidware and Digital Twins

The Fluidware vision is specifically meant to shine in highly dynamic large scale scenarios, such as those targeted by DT solutions, as reported in Section 7.2.3, where adaptation to run-time contingencies and changes is the norm rather than the exception [19]. A retirement facility for elderly people or people with chronic diseases, both requiring peculiar care and continuous assistance, would be a perfect example. Once the facility is disseminated with sensor and actuator devices, and a DT layer is laid on top, one can think of exploiting the Fluidware paradigm, for example funnel processes, to deliver monitoring and control services that seamlessly cope with changes in the application: new devices (and their DTs) joining of leaving the system, new people, even new functionalities required (via composition of funnel processes).

Another appealing scenario for Fluidware, and where DTs may serve the purpose of producing the event flows that Fluidware envisions, is a smart university campus. There, spaces could be re-organised on a per-need basis, such as in the case of planned temporary events (e.g., meetings, conferences, seminars, industry recruiting, etc.) or unexpected contingencies (e.g. cancellation of lectures, strikes, etc.). Services such as real-time tracking of rooms occupancy, adjustment of rooms' environmental conditions to the occupants' needs, a navigation system to steer people towards their destination featuring integrated contextual information such as current or future crowded areas, are all examples of functionalities having high dynamicity and calling for adaptation, hence suitable for the Fluidware approach.

7.4 Discussion

In this section we report about challenges that despite the effort from the research community, remain still open and that need to be addressed together with the presentation of some concepts that aim at enhancing the one of Digital Twin.

7.4.1 Challenges

Several challenges relate to the design and implementation of DT solutions [58]. In the following we do not report an exhaustive list but we focus on those that in our opinion are among the most influential.

Self-Development. Digital twins are not static entities but dynamic models that evolve over time. Digital twins are also being referred to as "living models" that continually adapt to changes in the environment or operation using real-time sensory data and can forecast the future of the corresponding physical assets [42] [35]. Therefore a way to introduce individual and collective self-development capabilities [16] [15] is required.

Dependability. Digital twin can be used for development of critical systems, with real-time constraints therefore they require efficient interworking functions between digital twins and the physical systems. The different kind of DTs that can be implemented in terms of resolution, complexity, modelling languages and formats and the lack of a standard. Large-scale digital twin platforms are required to include distributed digital twin cooperation framework, flexible data-centric communication middleware, and the platform based digital twin application to develop reliable systems. Many CPS vendors will provide vendor dependent digital twins and the interconnection between them is essential to make large-scale digital twin space [7].

Interoperability. Although the literature is conceptually aligned on the idea and the importance of DT [48], there is not yet a unifying model for representing and properly working with DT across multiple application domains. The fragmentation of existing solutions is mostly related to their specificity for a target sector, and creates an unnecessary substrate of heterogeneous proposals [59]. Currently, it is almost impossible to create an ecosystem where devices, services, and users can efficiently cooperate through a shared and interoperable DT vision. Nevertheless, both the industrial and academic worlds are moving towards this vision. The Industrial IoT Consortium, for instance, is proposing a shared reference architecture [43, 54] taking into account DTs relationships, composition, and main services (e.g., prediction, maintenance, safety).

The oneM2M organisation[1] and the World Wide Web Consortium [2] are also actively working to provide uniform access and description of physical assets to achieve practical interoperability across multiple application domains and deployments. However, the definition and role of DTs is yet unclear in these initiatives, e.g., the WoT sees DTs as a cloud-driven interaction pattern instead of a fundamental tool to digitise and model physical assets. A broader perspective is brought by the WoDT proposal [22], that shares many aspects with the Gemini Principles vision [9]. Essentially, both aim at building DT ecosystems where many DTs can serve multiple applications' requirements in a sort of "as-a-service" paradigm.

DT Deployment. The combination of IoT and DTs has traditionally happened through cloud-driven and domain specific architectures. This limits the potential of DTs by creating an unnecessary substrate of heterogeneous implementations [59]. There, in fact, latency issues may disrupt DTs purpose, as communication between the physical and the logical object is effective only if the refresh time is lower than the average access time of applications. Thus, it should be possible to deploy DTs as close as possible to the physical devices. Fog and Edge Computing [6, 10] overcome these limitations by enabling to operate with ultra-responsive and ultra-reliable connectivity in multiple operational contexts. The adoption of distributed DTs deployed on the edge already showed some interesting results in industrial deployments [7].

However, the following limitations still hold: (i) fragmented design and modeling; (ii) adoption of monolithic and centralized approaches; (iii) limited interoperability and heterogeneity management; and (iv) internet dependency and introduced delay. In this context, the characterization of the role, capabilities, and responsibilities of DTs running on the edge is still not well defined, structured, and experimented in the literature. A notable exception is the work with WLDT [23], that proposes last-mile digitalization and heterogeneity management through the deployment of Edge DTs operating as active entities close their physical counterparts.

Security. Security it is a challenge that needs to be addressed in all digital related sectors but given that digital twins are extremely tightened with the real world, digital Twins can be used not only to provide information for decision-making but also to make decisions and perform actions in the physical world, security is even more relevant in reference to digital twins. Identifying the role that security systems and technologies such as blockchain will play is of fundamental importance for the realization and implementation of Digital Twin solutions. We can learn from studies targeting Security of IoT platforms [9].

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[1] `https://www.onem2m.org/`

[2] `https://www.w3.org/`

7.4.2 Advanced Digital Twin Concepts

To address some of the above challenges, new concepts that enhance the one of Digital Twin are being proposed by the literature.

Opportunistic Digital Twin. The need of infrastructures focused on specific sensing tasks and powerful enough for promptly processing big amount of data hinder the development of key IoT services, especially those particularly complex and large scaled typical of smart cities. In this direction, a concept of Opportunistic Digital Twin has been defined at the confluence of DT, synthetic sensing and Edge Intelligence (EI) aimed to simplify the (re)engineering of large-scale distributed smart systems by moving complexity from hardware infrastructure to software layer. The synergic exploitation of DT and EI techniques promises to ease both the representation and the programming of complex environments by providing straightforward metaphors for virtualizing any-scale infrastructures as well as a sound basis for injecting intelligence into its operation systems [8]. Collecting simple data from the environment and by opportunistically elaborating them through AI techniques directly at the network edge, a digital version of a physical object can be built from the bottom up as well as dynamically manipulated and operated in a data-driven manner, thus enabling prompt responses to external stimuli and effective command actuation [55].

Cognitive Digital Twin. Recent advancements in IoT, big data, and machine learning have also significantly contributed to the improvements in DTs regarding their real-time capabilities and forecasting properties. Collected data constitute the so-called digital threads and are the grounding information on which simulation or machine learning algorithms rely to make predictions, enabling failures to be anticipated, to optimize the system, to design novel features, to ease and accelerate decision making, and to improve productivity. Whenever DTs encapsulate reasoning capabilities, the concept of DT has evolved into Cognitive Digital Twin (CDT) [1, 21] that has been introduced in the literature to refer to those DTs that autonomously perform some intelligent task within the context of the physical asset, related to, e.g., smart management, maintenance, and optimisation of performances. Cognitive Twin or Intelligent DTs [29] are indeed, the most advanced examples of DTs, are defined just in the context of IoT Platforms and leveraging on their connectivity, analytics, simulation and visualization tools.

7.5 Conclusion and Future Work

In this chapter we focused on Digital Twins, highlighting the interest that such a topic is attracting together with the convergence with the Fluidware project and related results. We initially reported a description of concepts related to DTs such has DT characteristics, their enabling technologies and some usage scenarios. We then described those results of the Fluidware projects that contribute to the topic of

Digital Twin. We then discussed additional challenges of DTs together with emerging concepts that enhance the concept of DTs.

From our analysis of the literature it emerges clearly that a lot of interest is directed towards the DT topic with several research papers being published. What is missing is actually real and documented implementations of those concepts in complex scenarios. The community should start implementing what has been proposed so as to validate the approaches and highlight possible critical issues. We urge initiatives that allow different communities to work together to carry on projects in order to make the most of this innovative drive and this particular interest in the topic of Digital Twins.

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