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► **To cite this version:**

Roberto Minerva, Noel Crespi. Digital twins: properties, software frameworks, and application scenarios. *IT Professional*, 2021, 23 (1), pp.51 - 55. 10.1109/mitp.2020.2982896 . hal-03210180

HAL Id: hal-03210180

<https://hal.science/hal-03210180>

Submitted on 27 Apr 2021

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Digital Twins: Properties, Software Frameworks, and Application Scenarios

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Abstract—The Digital Twin (DT) is an emerging approach that promises to change the way products and systems are made and used. The DT is attracting increasing interest in the Internet of Things community for its potential applications. Despite the hype, this approach requires a more precise definition and characterization in terms of its properties in relationship to software architectures and their platform implementations, as well as a deeper analysis of its potential applications and actual feasibility in several industries. This paper investigates the basic properties that hold for a DT, sketches a software framework and presents two application scenarios. The paper also addresses the business impact of DT by discussing servitization capabilities.

■ **THE DIGITAL TWIN (DT)** was conceived to design, prototype, and operate a virtual copy of a product.¹ It promotes the softwarization of physical objects (POs), into logical components and the development of applications that exploit programmability of the software representation. Originally used by NASA,² it has gained interest in manufacturing.³ Because of its ability to describe POs by means of logical models and actual data, it is increasingly used in the Internet of Things and cyber-physical

systems.⁴ To fully master its potential, there is a need to understand what a DT is from a software perspective, how to support and implement it, how to manage the physical and logical counterparts, and what constraints are implied by the relationship between them. This article addresses the current DT definition, and identifies a set of characterizing properties. Next, a software framework is sketched out to illustrate two application scenarios that highlight technical possibilities and challenges. An analysis of some business benefits is provided. Conclusions summarize challenges and risks of this approach.

Digital Object Identifier 10.1109/MITP.2020.2982896

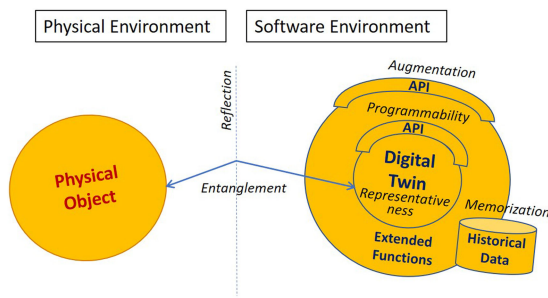


Figure 1. DT representation.

DIGITAL TWIN (DT) AND ITS PROPERTIES

DTs embody software capabilities to describe or simulate relevant features and behavior of POs from design to end-of-life phases.⁵ A DT is a software actionable representation of a PO (or aggregated objects) in a specific environment. Some PO's features could be unrelated to the goals of the software representation. Products or complex objects are the main targets, because mapping one to one atomic objects may be unpractical or useless. DTs in a cyber-physical systems (CPS) domain are characterized⁶ by events they are capable of managing, methods and functionalities they offer, storage capabilities to maintain a historical log of status changes, ability to serve as functional interfaces to applications through application programming interfaces (APIs) and ability to send/receive information. The definition of basic DT properties (see Figure 1) is instrumental to determine requirements and constraints posed to software platforms. The key properties of a DT are given as follows.

- *Representativeness and contextualization.* A DT represents the PO in a specific context, i.e., a DT is a software implementation of a model representing the PO in a specific environment. Feature simplifications or generalizations are possible when they do not affect the behavior in the specific context.
- *Reflection.* A DT mirrors the behavior and the status of the PO. Each change in status, each event faced by the PO is reflected by the DT. Changes that occur to the DT should be reproduced in the PO.
- *Entanglement.* A DT and its PO must be constantly “connected” to instantaneously (i.e., in a time period consistent with requirements

of applications) register any change in status. Entanglement requires an effective, reliable communication between the PO and the DT suitable to the rate of changes.

- *Persistency.* A DT is always available. Its availability exceeds the actual existence of the PO. A DT could be available before the “creation,” during malfunctioning and crashes, and after the end of life of the PO.
- *Memorization.* A DT stores all the status changes and events occurred to the PO. A DT represents the status of the PO over time and space.
- *Augmentation.* A DT can extend the PO functions and offer them by means of APIs. Augmentation can add new functionalities that the PO does not support or provide access to data in particular formats.
- *Composability.* Physical systems are aggregations of subsystems and components, a DT must support the correlation of different elementary DTs into complex organizations and provide views on the aggregated DT and individual components.
- *Replication.* A DT can be replicated to serve the needs of different applications. Replicas of the same PO must behave consistently, i.e., they cannot have a different status and they cannot exhibit different behaviors.
- *Accountability/Manageability.* Each DT must be manageable; it is possible to determine its status and activities and to optimize its execution in the framework in which it is operating. It must provide information about the usage of the PO by the applications associated with it. Self-management of DTs is a desirable property for large systems.
- *Servitization.* A DT enables the transformation of a product/artifact into a set of functionalities offered to users. This capability transforms products into software-controlled and connected entities accessible “on-demand” by users.
- *Predictability.* A DT has the ability to simulate its behavior over time. Specific instances of DTs can simulate the behavior of PO in a context at a specific time (in the past or in the future).

Some DT properties need contextualization: replicas are used for tracking POs or for simulate

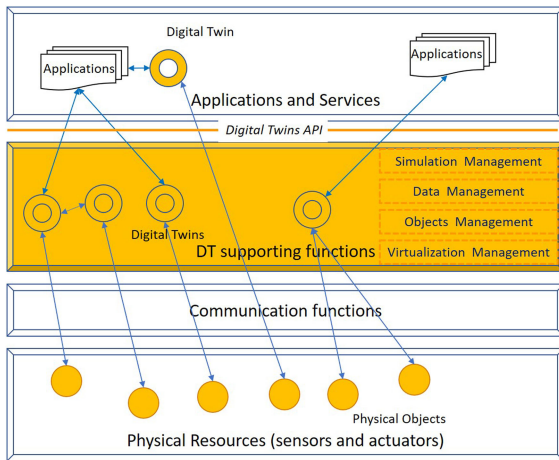


Figure 2. General framework for digital twins.

128 their behavior. All the replicas of a DT tracking
 129 the actual status of a PO should have the same
 130 status at the same time t (with time limitations
 131 explained for entanglement), DTs used for simu-
 132 lations can diverge depending on the simulation
 133 conditions.

134 TOWARDS A GENERAL SOFTWARE 135 FRAMEWORK

136 A software framework for DTs implements
 137 numerous functionalities, e.g., orchestration of
 138 objects, cognition for intelligent optimization,
 139 self-management to minimize human interven-
 140 tion. Different software architectures may be
 141 applicable.^{7,8} Some adopt layering principles for
 142 organizing functionalities.⁹ These architectures
 143 must be evaluated to determine how properly
 144 they support the DT requirements. Figure 2 rep-
 145 resents a generic framework organized in four
 146 functional segments. This structure is chosen to
 147 illustrate the separation of concerns. IoT devices,
 148 communications means (protocols and net-
 149 works), DT tools and functions will quickly
 150 evolve. Layering may prove useful: it is simple
 151 enough to be practically used and can allow
 152 independent evolution of the different techno-
 153 logical layers. Finally, layering is aligned with
 154 efforts in standardizing IoT architectures. AIOTI¹⁰
 155 describes an IoT layered architecture that could
 156 support the DT approach. However, modulariza-
 157 tion and linkage of functionalities can prove as
 158 practical as layered architectures. Physical
 159 resources are devices producing information or

160 acting on the environment (sensors and actua-
 161 tors). The information (commands, events,
 162 requests, and status notifications) exchanged
 163 between devices and components of the frame-
 164 work is transported by means of communica-
 165 tions functions. The DT supporting functions segment
 166 represents the execution environment of DTs
 167 and the set of intelligent functionalities that DT
 168 instances use for orchestrating their interactions
 169 and lifecycles (e.g., instantiation, replication,
 170 identification, access control, and self-manage-
 171 ment), managing collected data, and simulation
 172 capabilities. This segment mediates the interac-
 173 tion between applications and physical devices.
 174 New functions, mechanisms and tools may be
 175 progressively designed and added to better meet
 176 DTs requirements. The application and services
 177 segment supports the applications that use the
 178 DTs interfaces and functions. For customization
 179 and execution purposes, DT replicas may be
 180 locally executed in this environment.

181 The actual exploitation of the DT as a general-
 182 purpose approach occurs if some conditions are
 183 met: the availability of a software framework
 184 capable of fulfilling the properties of DTs; the
 185 ability to create new applications with better
 186 functionalities for the user; and the ability to
 187 introduce new business models or to improve
 188 existing ones. These issues are analyzed in the
 189 following sections.

190 APPLICATION SCENARIOS

191 DT can be used to implement several scenar-
 192 ios. In this article, two application scenarios,
 193 based on properties of DTs and software frame-
 194 work, illustrate possibilities and issues.

195 *Scenario 1: Virtual Object*

196 This example describes how to create the DT
 197 of an object. A sensor is chosen, but different
 198 (aggregations of) objects may be considered.
 199 The needed design tasks are given as follows.

200 *Physical object model:* An abstract computable
 201 description of the data and behavior of the PO
 202 that the DT implements. The sensor status and
 203 the measurements it takes in the environment
 204 are relevant aspects to consider and to model.

205 *API definition:* an interface for requesting the
 206 functionalities offered by the DT. Applications use
 207 it to get data or to give commands. Data formats
 208 and interaction mechanisms should be defined.

Entanglement model: a model governing how PO and DT exchange data and status updates. The framework must offer mechanisms and protocols to support communication. Often the data flow is unidirectional from PO to DT, while it is bidirectional between the DT and applications (data, events, and commands). Commands from the applications to DT are used to govern the DT behavior.

A single PO can be replicated by several DTs. This occurrence accommodates specific requirements of applications: providing special functions, or permit access to the data with different rates, or segmenting and securing the computational space. Replicas can be instantiated in the framework and others in the application space. This option offers flexibility in deployment. Replication of DTs poses interesting issues. When the status of the PO changes, all the replicas need to change status. The propagation of information can be achieved with different mechanisms; PubSub is used in IoT implementations¹¹ and it suits the case of unidirectional communication (where the PO is a publisher and the replicas are subscribers). If PO status can be modified or it can be instructed (an actuator), the problem of synchronization and consistency of information between the PO and different replicas emerges. This issue can be solved by introducing transaction management functions into the framework.

Scenario 2: Digital Twins in Smart City

Cities are complex systems¹² difficult to control and program. A prerequisite for a smart city is having “measurable” attributes. Sensors and actuators are deployed to capture data that describe its processes. This make a city quantifiable and assessable. Once reliable data are available, artificial intelligence and machine learning, AI/ML, techniques determine patterns and behavioral models of urban systems.¹³ The city becomes “understandable,” i.e., it is possible to predict events and their associated causes by means of data analysis. DTs are a step toward the programmability of a city: the digital representation of resources makes it possible to design applications that, by interacting with DTs, can affect the behavior of “things” and optimize city resources and their behavior. Several experiences introduce the DT concept in smart

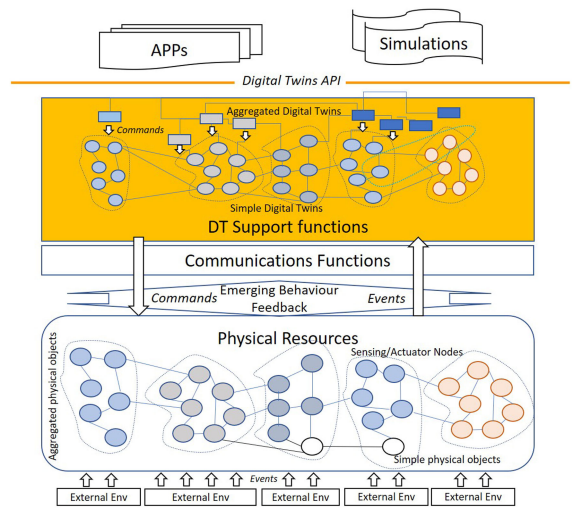


Figure 3. Programmability of complex systems with digital twins.

cities.^{14,15} The DT application introduces new capabilities and has an impact on how to govern the complexity of urban systems. For example, the adoption of the DT approach is improving the usage of building information modeling, e.g., such as given by Delbrügger *et al.*¹⁶

DTs are programmable objects that can orchestrate, on request of applications, POs like actuators toward the desired behavior. DTs can detect malfunctioning in POs and minimize their impact on other resources. DTs, exploiting advancement in storage technology, can store large datasets and hence supporting the continuous “learning” of city behavior. They offer the possibility to evaluate new policies by simulating future situations. DTs could be utilized to solve a common issue of smart cities: the siloing of application domains (e.g., transportation, energy, and so on). DTs offer interfaces through which different applications can access data, behavior, and status corresponding to specific resources. DT composability enables the creation of object aggregations that support abstract views of larger phenomena. The framework must scale up from few resources to a multitude. Figure 3 represents a DT platform able to capture the behavior of a complex system. Some applications are designed to monitor the situation for applying policies on specific issues (traffic, transportation, etc.). When issues arise, these applications implement mechanisms to minimize impacts on users and optimize

291 resource usage. Other applications are simula- 338
292 tions executed to understand how the “smart 339
293 city” could react to changes in policies of 340
294 resources’ usage. Benefits of applying the DT 341
295 concept to the “smart city” are many. These 342
296 advantages depend upon the introduction of 343
297 higher programmability levels, a strong integra- 344
298 tion with AI/ML capabilities, the elimination of 345
299 silo constraints, and the possibility to simulate 346
300 the functioning of a city. 347

301 BUSINESS AS USUAL? 348

302 The DT concept has business implications. It 350
303 changes the nature of POs and products. DT 351
304 properties facilitate the adoption of servitiza- 352
305 tion, i.e., the ability to transform a physical prod- 353
306 uct into a set of services offered to the user.^{17,18} 354
307 Servitization nurtures customization of function- 355
308 alities, making products more aligned to the life- 356
309 styles and needs of people and it introduces 357
310 additional innovations in the service area.¹⁹ 358
311 Products could even be modified, improved, and 359
312 customized by the user. New functions can be 360
313 added to products if users’ needs change. The 361
314 customer relationship process could be trans- 362
315 formed.²⁰ Customers are “entangled” with prod- 363
316 ucts. If malfunctions emerge in a product, they 364
317 can be predicted before they actually occur and 365
318 the impact on users could be mitigated. Mainte- 366
319 nance can be improved by focusing more on pre- 367
320 venting problems than on solving them. The 368
321 products’ value chain could be largely modified. 369
322 As the mobile phone industry showed, a rich 370
323 application layer has a tremendous impact on 371
324 products and it can determine success in a 372
325 global market. Customization, and the actors 373
326 supporting it, could become an important com- 374
327 ponent of the entire value chain of new digital 375
328 markets. 376

329 CONCLUSIONS 377

330 The DT approach promises to have impact. It 378
331 may provide solutions in different sectors (smart 379
332 cities, e-health, e.g., virtual patient, automotive, 380
333 cultural heritage), supporting the provision of 381
334 servitized products, and programmability of 382
335 complex systems. It fosters new ways of doing 383
336 business by transforming products into sets of 384
337 customizable services (an autonomous car and a 385

smart building). A precise definition of the DT 338
can help in better understanding requirements 339
and impacts on IoT software platforms. DTs 340
should be evaluated for their ability to support 341
and deliver the expected benefits. Further inves- 342
tigation on how DTs can enable an ecosystem of 343
applications that are feasible, marketable, and 344
sustainable by the industry is needed. There are 345
two major concerns: feasibility, i.e., the complex- 346
ity and technical challenges associated with the 347
creation of scalable, secure DT frameworks are 348
such that the construction of a viable platform 349
remains to be proven in-the-large; and user own- 350
ership, i.e., the possibility to frame users into a 351
system of products and applications that limit 352
privacy. The DT approach needs validation 353
before it will be widely accepted and used. It 354
already is a powerful means to control, govern, 355
and program the lifecycle of objects, physical 356
resources, and products, for providing better 357
services to end-users. It is a challenge to acade- 358
mia and industry to find relevant applications 359
for it. 360

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