Digital Twins —
Classification and Examples

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Summary

Diverse technical applications utilize digital twins. However, the term “digital twin” encompasses a wide spectrum of meanings, often lacking clarity regarding its specific attributes, and what parts of the real system it represents. This paper proposes a classification of digital twins based on two criteria: the type of communication between the digital twin and reality, and the simulation speed at which the digital twin mirrors reality. This classification is supported by numerous practical examples illustrating the classification.

1 Introduction

During the Apollo 13 mission to the Moon in 1970, technical issues with the service module necessitated an in-flight abort. The revised plan was for the capsule with the service module and lunar module attached to orbit the Moon and then return to Earth. Initially, determining how to operate the engines for this trajectory was a challenge. What happened next was perhaps the first documented use of a digital twin: Houston's Mission Control assessed the spacecraft's current position, velocity, and the altered configuration with the lunar module attached. Using this data, they calculated a revised course back to Earth and devised precise thruster usage timings to correct the trajectory. These simulations, conducted on a NASA computer, provided crucial guidance to the crew inside the space capsule. Ultimately, this innovative procedure proved successful, enabling the safe return of the crew to Earth.

Okay, Houston — we've had a problem here.
Jack Swigert

So, what happened? The behavior of a spacecraft within the gravitational fields of both the sun and the moon were calculated with a computational model, and communication took place from reality to the program (regarding the position and speed of the spacecraft). Upon computation, directives were transmitted back to the spacecraft. Moreover, the system was able to respond to unexpected requirements, such as the new course or mass of the shuttle with the lunar module docked. This is how we envision a digital twin today!

Of course, the term "digital twin" was not in use in 1970. It appeared later in a NASA publication in a different context and has been widely used in various publications in recent years. However, its usage varies significantly. In the context of Industry 4.0, for example, the term is used as a digital replication of a real process operating as software in tandem with the actual system and engaging in data exchange with it. In the Industrial Metaverse environment, on the other hand, the focus is on interaction with people, and a real system is not assumed.

The German "Gesellschaft für Informatik" gives the following description in its dictionary of Computer Science, available on its website: [1] "Digital twins are digital representations of things in the real world. They describe both physical objects and intangible entities like services, providing comprehensive information and functionalities through a standardized interface. For the digital twin it is irrelevant whether the counterpart already exists in the real world or will exist in the future". As you can see, the term "digital twin" is used very broadly. It is therefore useful to classify it to better understand what is meant by a digital twin within various contexts.

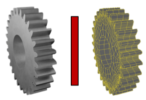
The objective of this white paper is to categorize various digital twin variations and explain them with practical examples. While their application for services is overlooked, the emphasis is directed towards digital twins associated with real objects.

Initially, we will categorize digital twins based on their communication with the actual system. We distinguish between digital twins that

- operate independently without any communication with the real system,
- solely receive data from a real system without transmitting any information back,
- engage in bi-directional communication with a real system.

The working group on Digital Twins within Industry 2025 [2], for instance, identifies bi-directional communication as an essential characteristic of a digital twin. However, our interpretation here diverges from this definition, focusing instead on practical usage. Alongside the categorization based on communication capabilities, we also distinguish whether the digital twin operates synchronously with the real world (i.e., in real time) or not.

2 Digital Twins without communication



We first consider the digital twin without communication with a real system. In this scenario, the absence of real-time communication negates the necessity for an actual physical counterpart. Classic examples are simulation models that have been used in product development for years. These include finite element models, which describe the mechanical behavior of real objects in order to test their function and limits in advance, and to enable product optimization. The allure of these methods is that they can be used very early in product development to evaluate and optimize the design without relying on prototypes. It's important to note that these digital systems typically do not operate in real time; instead, simulations might necessitate extensive computing durations.

Intelligent digital twins are changing how businesses operate, how they collaborate and how they innovate – and enterprises that get left behind will struggle to participate in the markets and ecosystems of the future.
Accenture Tech Vision Report 2021

Let us consider the antenna on board of the JUICE spacecraft [3], which embarked some time ago on a mission to explore Jupiter's moons, where ice is suspected to exist. The radar comprises a 16-meter-long dipole antenna, necessitating a folding mechanism. The company Space-Tech's innovative design employs a combination of carbon fiber tubes, enabling them to fold through recesses within their midsections. When folded in, they're tensioned like a spring and can then be unfolded in space without the need for additional energy. This design boasts an incredibly light weight, merges the electrical conductor into the mechanical structure, and features an energy-efficient folding system. Mechanical simulations can be used to analyze the dynamic behavior of the system and to optimize the design of the recesses with respect to the mechanical stresses. The risk of cracking is greatest at these locations. Figure 1 illustrates the outcomes of a mechanical simulation analyzing the joint within the tubing.

Flight simulators serve as another example of a digital twin operating independently without communication. They are instrumental in training pilots to operate passenger aircraft effectively. These simulators precisely replicate the physical behaviors of an aircraft in real-time, responding dynamically to pilot inputs. They've become a cornerstone of pilot education, offering meticulously detailed recreations of significant portions of the cockpit. However, the intricacy and fidelity involved in replicating these components contribute to the considerable expense associated with these flight simulators.

Reishauer AG has taken a different learning approach with a digital twin in collaboration with ETH and RhySearch [4]. They've created a virtual representation of a Reishauer grinding machine accessible through VR glasses. Remarkably, the simulation model integrates the actual control software of the grinding machine, ensuring that the virtual model mimics real-world behavior. This immersive experience enables users to learn machine operation without the necessity of a physical machine. The flexibility of

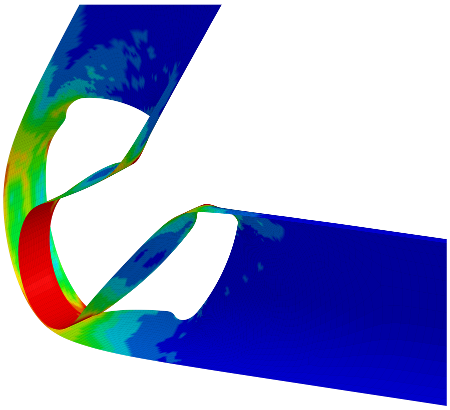


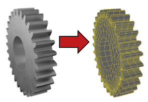
Figure 1: Simulation of the folding antenna (half model) of JUICE. Illustration of the equivalent stresses.

this virtual setup enables learning from anywhere and facilitates multiple practice sessions. Consequently, it offers a cost-effective learning solution, allowing users to tackle complex scenarios without risking damage to an actual machine. Figure 2 gives an impression of the learning environment.

Figure 2: Virtual learning environment with a grinding machine from the company Reishauer AG.

A final example of digital twins without communication with the real system are the models in the industrial metaverse [5]. These are models of systems with real graphical representations that interact with the user, typically wearing VR glasses. This allows a human to move around with robots in a production environment, to optimize human-machine cooperation, or to test the behavior of automated robots in the presence of humans. Obviously, the models in this scenario operate in real time. In the industrial metaverse, the focus is on the interaction of digital twins with humans, not on communication with the real system.

3 Digital twins processing data from the real system



Now we will discuss digital twins that receive information from the real system, but do not establish a communication channel back to the system. The following are three typical applications:

- Inverse problems
- Virtual sensors
- Predictive Maintenance

3.1 Inverse Problems

The term "inverse problem", which originates from mathematics, describes tasks in which data is measured in reality and an attempt is made to determine information about the causes of the data [6]. This abstract description is illustrated by a well-known example: During medical ultrasound examinations sound waves are directed into the body, some of which are reflected at the boundaries between tissues and organs. The other part components of the waves continues to travel until they reach another boundary surface. The transducer measures the reflected sound waves. This measurement method determines the time it takes for the sound waves to travel through the tissue.

In most of these presentations, the words Digital Twin can be easily replaced by something that is more thoughtful and pragmatic such as model, information, simulation, etc.
Oleg Shilovitsky

The exact path that the sound waves have taken in the tissue is initially unknown. This is where mathematics comes in: In a simulation model, organs and tissues are positioned so that the simulated ultrasound travel times match the measured travel times. The outcome – identifying organ and tissue boundaries – is then presented to the doctor on a monitor during the examination. The digital twin effectively mimics the ultrasound's propagation, including reflections, operating in real-time to enable swift medical assessments.

There is also a large and slow variant of this principle: seismic measurements. The objective here is to detect the boundaries between layers of rock within the Earth, such as locating mineral deposits or assessing the viability of subsurface conditions for a geothermal power plant. The principle is similar to that used in medicine: sound waves are emitted at various points by employing sizable vibrating plates affixed to a truck, generating vibrations. The resulting sound is captured through numerous geophones placed at various locations. Such a survey typically covers several square kilometers and takes several weeks. The analysis, involving the solution to the inverse problem, is complex and often extends over several months. Figure 3 shows a subsurface model of the type used, for example, to simulate seismic behavior.

In practice, digital twins can help organizations create more agile operations, mitigate future risks and remain competitive in an increasingly complex and unpredictable business environment.
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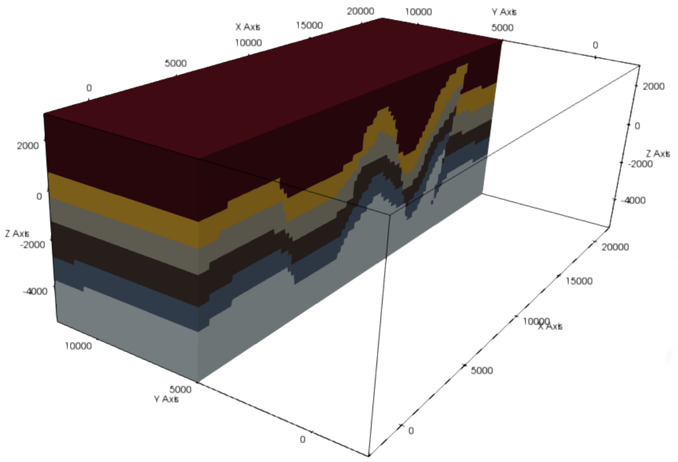


Figure 3: Subsurface Model. Seismic methods are used to obtain information about the subsurface.

3.2 Virtual sensors

Virtual sensors are used when a quantity is measured on a system to determine another property with that quantity. This requires a model that can derive the desired value from the directly measured value. Depending on the complexity of the task, a digital twin is used.

A very simple (almost trivial) example is a thermistor. It is used to measure temperature. It consists of a conductor whose resistance changes with temperature. The temperature is deduced from the measurements of the electrical values. A characteristic curve relating the electrical behavior to the thermal behavior is the basis for this. You could call this situation a digital twin using a characteristic curve, as is common in metrology. This is unusual, but it shows that the definition of a digital twin given above is broad enough to cover these cases as well.

Digital Twin is a cool name. I hope you agree. And I like this name. Unfortunately, marketing did their job well and created a glorified definition and campaigns about Digital Twin that is very confusing.
Oleg Shilovitsky

A better example of a virtual sensor is the Hot-Disk sensor [7], used to determine the heat capacity and thermal conductivity of materials. The principle of operation (Figure 4) can be described as follows: By passing electric power through a conductor clamped between two samples, the conductor and consequently the sample are heated through heat conduction. The specific ohmic resistance of the conductor depends on its temperature, enabling the indirect measurement of the sensor's temperature through electrical parameters. Thus, at the center of the sample, there is a heater with a known power, while simultaneously being able to measure the temperature of the sample. The temporal evolution of the temperature can then be analyzed to infer the material properties of the sample. This relies on a deep understanding of how heat propagates within the sample based on material parameters. Currently, at RhySearch, we are working on enhancing this digital twin to measure anisotropic material properties as well [8].

3.3 Predictive Maintenance

Figure 4: Hot disk sensor. On the left you can see the sensor clamped between two samples, on the right detailed images of the sensor.

A common application of digital twins is predictive maintenance. The goal here is to predict the lifetime of components or systems in order to determine the optimum time for maintenance work. The development of data-related digital twins for this purpose is very challenging:

Still, digital twins are more than just an evolution of digital models, although their goal is similar: Higher quality products and better product support at less cost and less effort.
Michael Park

- In practice, machines are usually not operated until a component fails. Therefore, there is often little or no measurement data available from the machine regarding when it is about to fail.
- The output of the digital twin is of a statistical nature. In order to determine the quality of the digital twin, the system must be understood well enough to describe the probability of a component failure if the digital twin recommends maintenance. In other words, you need the conditional probability distribution for a failure, assuming that the digital twin recommends maintenance.

These difficulties make the development of data-related predictive maintenance systems is very demanding and time-consuming.

The following example illustrates how the combination of physical simulations and experiments for predictive maintenance can be successful: To predict the service life of mechanically stressed components that are exposed to dynamic loads, we are interested in the mechanical stresses that occur in the component and how the evolve over time. The critical points on the component are often known, but it is not possible to measure stresses or strains there. It is only possible to measure the displacements or strains at other points in the structure. A finite element model that simulates the behavior of the component can now help. The measured displacements or strains are entered into the simulation model, which calculates the stress curve at the critical points and estimates the remaining service life. To estimate the service life, results from vibration tests on materials are typically used to calculate the Wöhler curve [9]. Figure 5 illustrates a situation in a generic case.

Mechanics is the paradise of the mathematical sciences because by means of it one comes to the fruits of mathematics.
Leonardo da Vinci

It is often desirable for this simulation to run in parallel with the real situation. For this purpose, it may be necessary to compute a so-called reduced model rather than the complete simulation model. For model reduction [10], there are the classic methods of model order reduction (MOR) in the linear case, which is often already integrated in the finite element software. The situation is more challenging in the non-linear

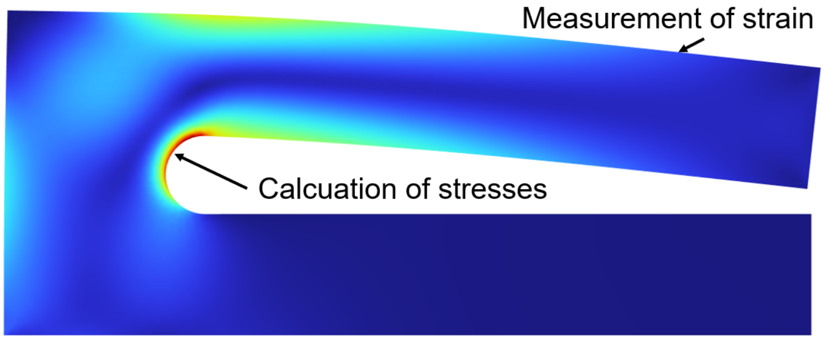
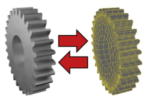


Figure 5: To obtain information about the stress on the left, strain measurements are taken at other points. Using a finite element model, the digital twin is able to infer the stresses at the critical point from the history of the measured strains.

situation, for example with complex material behavior, or if there is a so-called contact problem where components touch each other. In this case, specific methods must be used on a case-by-case analysis. A more recent trend is to use artificial intelligence methods for these problems. The neural networks are trained in advance with a wide variety of situations (often with results from simulation programs), so that they can be evaluated in real time during operation. Or physical principles are incorporated into the training of neural networks. These "physically informed neural networks" are still the subject of current research [11].

4 Digital twins with bidirectional communication with the real system



Of course, digital twins with bi-directional communication to the real system only work if the digital twins can operate in real time. The basic concept in this category is that real systems provide data to the digital twin, calculations are performed there, and this data is fed back to the real system. One significant application of this technology is "model-based control". In this approach, data from the digital twin is used to influence the real system. This goes beyond what can be achieved with "classical" control engineering. By virtue of the digital twin accurately representing real behavior across multiple facets, the controller has access to a wealth of information, enabling the realization of more effective control strategies.

A great example of this can be found in modern coffee machines: The quality of the coffee greatly depends largely on the temperature of the water as it passes through the coffee grounds. However, due to technical limitations, the water temperature is not measured directly at the coffee grounds but much earlier in the system, close to the water tank and pump.

Deriving the water temperature at the coffee grounds from the water temperature at the pump is not straightforward. Factors such as whether the machine is preheated, whether coffee has been brewed recently, the room temperature, the output of the heating block, and more all affect this. Therefore, the role of the digital twin is to estimate the water temperature at the coffee grounds by measuring the water temperature at the pump, pump operation, and heating block usage. This allows for optimal control of the machine's heater block by simulating relevant aspects of reality and behavior in real-time, running parallel to reality.

Other examples of using digital twins can be found in manufacturing machines. Their heating during operation can lead to thermal expansions that negatively affect machining quality. This can be compensated if not only the temperature is known, but also the mechanical situation with its distortion can be represented in a digital twin. This is a current research topic that we are working on at RhySearch.

While there are multiple ways of solving these problems, the use of „digital twins“ is gaining traction.
Accenture

5 Conclusion

The term "digital twin" is not used consistently in practice, so it is often unclear which aspects of reality the digital twin represents. This paper classifies different digital twins based on two aspects: the type of communication and the speed at which the digital twin simulates aspects of reality. By merging physics-based simulation methods with artificial intelligence techniques, digital twins are expected to be found in numerous other applications in the future. It remains to be seen what the future holds.

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