# Digital Twins

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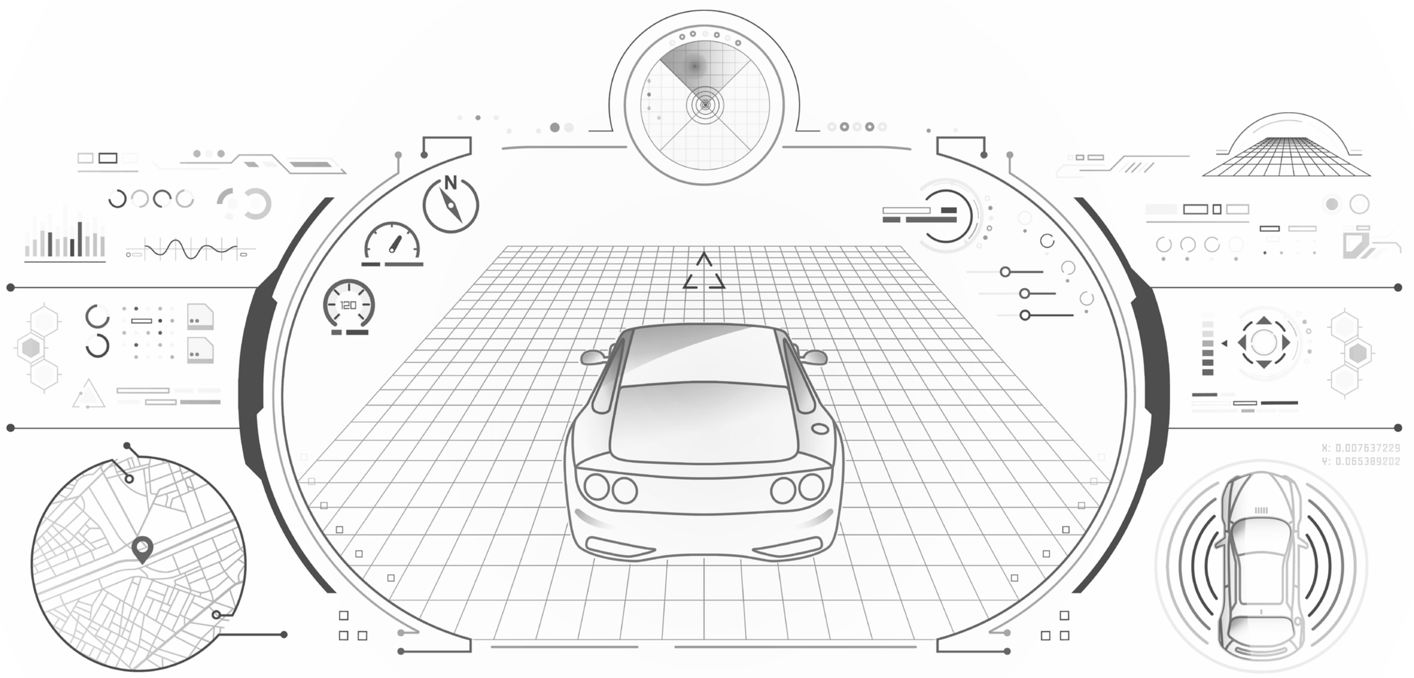

# Digital Twins

*Virtual representation of physical systems*


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**Dr. Deniz Iren, PMP**
Center for Actionable Research of Open University (CAROU)
Department of Information Sciences, OU
deniz.iren@ou.nl

Remember Tamagotchi, the virtual pet that lives inside a digital key chain? Just like a real pet, it would go hungry, thirsty, and crave for attention. Now imagine that Tamagotchi was the avatar of a real pet… Connected via sensors, it would mimic certain behaviors and states of the actual pet in real-time. For instance, when the pet sleeps, it would sleep on the pixelated screen, and when the pet does not eat for a long time, it would appear famished. Now that would be an excellent example of a digital twin.

A digital twin is a virtual copy of a physical system. It is a replica that lives inside a computer. By exchanging data with the real-life system via sensors, the digital twin displays the current state of the actual one. Moreover, the digital twin behaves similarly to the physical system which makes it possible to run simulations, and in certain cases, control the physical twin through the software interface of the digital twin. This whitepaper aims at shedding some light on the digital twin concept, laying out what businesses can expect and how they can implement and benefit from digital twins in any domain.

## Novelty

*How new is the digital twin concept?*

This exciting and beneficial technology is not actually so novel. The fundamental functionalities of digital twins such as modeling and simulation have been around for a very long time. However, the technological advances in sensors, Internet of Things (IoT), data visualization, and predictive analytics make digital twins more powerful, accessible, and popular today.

Every passing day, the coverage and bandwidth of Internet connectivity increase as the cost of transferring and storing data decreases. This trend seems to continue in the foreseeable future. These conditions provide an excellent opportunity for IoT. As of 2021, there are around 30 billion devices that are connected to the Internet, and this number is expected to grow in a non-linear fashion. This tremendous connectivity paved the way of the fourth industrial revolution, otherwise known as Industry 4.0. These developments turned the spotlights onto the key enabler technologies such as digital twins, and contributed to an increase in their popularity.

Another important trend that empowers digital twins is the growing maturity of data analytics and machine learning. The sensors of the physical system generate data at high volume, variety, and velocity. The analysis of such big data enables innovative service models such as predictive maintenance. Moreover, a comprehensive analysis might uncover bottlenecks, thus, making it possible to improve the efficiency of the system. As data accumulates, the digital twin continues to learn the patterns, whether they relate to a natural phenomenon or the behavior of the physical system's actors.

Finally, the state-of-the-art data visualization methods, augmented reality (AR), and virtual reality (VR) provide an unprecedentedly rich experience while interacting with the digital twin, and in turn, with the physical system. Such immersive technologies may ease the monitoring and control of highly complex systems. Moreover, they can provide a realistic training environment for key personnel even from remote locations.

## Functions

*What are the functions of digital twins?*

The most essential use of a digital twin is to visualize the state of its physical counterpart in a digital environment. However, it is not limited to a mere display of the current state. The functionality of digital twins encompasses past, present, and future.

The digital twin can use the historical state-data to "replay" the status changes that occurred in a given time period in the past. This allows the users to observe complex network of events and visually analyze the state change and diagnose how the unexpected states were reached.

The present-time state display shows what is currently happening on the actual system. In certain cases, in which there is a two-way data exchange, users may also control the physical system remotely via the interface of the digital twin.

Most modern digital twins also embody an Artificial Intelligence (AI) component that enables predictive analytics. Based on the historical and current state data, the digital twin can run simulations, predict which state-changes will occur, and display the ultimate state of the physical system at a given time in the future.

## Complexity

*How complex is a digital twin?*

The complexity of a digital twin depends on the complexity of the real system and the degree to which that system is modeled. The digital twin of a powerplant and a washing machine would probably be significantly different in terms of complexity. However, the real difference of complexity depends on the aspects that are captured by the digital twin.

By definition, a digital twin is a model. Just like every model, it is an abstract representation of reality. A model can be very complex but it is always simpler than the real system itself. For instance, the little depiction of a car on the dashboard of your real car shows you with LED lights the states of the doors of the real car. It only captures the state of the doors from just a few sensors. However, if you have paid attention when you took your car to a mechanic, you might have seen the complexity of the diagnostic systems that they use while checking the status of your car. Those digital twins are able to access most of the electrical components in a car such as the battery, and many mechanical parts such as the engine and the brakes. Thus, it is the degree of abstraction that determines the complexity of a digital twin.

## Value

*What value can you expect from digital twins?*

Having a digital replica of a complex system makes certain activities easy to perform which are otherwise even impossible. Think about climbing up a 150m tall wind turbine every time you need to measure the vibration or run any type of diagnostics. With a digital twin, all sensor and environmental data are in front of you, arranged and visualized in a way that they are understandable with basic intuition. It takes no more than a few clicks or taps to have a complete system checkup. In large-scale digital twins, users can see a vast variety of data aggregated and displayed on a model. For example, on a smart city digital twin, it is possible to see status data collected from a wide geographical area, and visualized in a concise manner to be understandable without much need for further analysis.

Generally, the digital twin interface mimics the appearance or the schematics of the physical system (e.g., Figure-1). The display of multiple aspects of the physical system together helps the user to build a visual relationship between events and have a better understanding of the overall system dynamics. This makes digital twins very useful in the training of key personnel that work with the physical system.

The real-time display and visualization of events and changes happening in the physical system, allows for a better understanding of processes underlying those events. It makes the bottlenecks of the processes clearly visible and assist users to identify improvement opportunities in terms of efficiency.

The traditional approach to industrial machinery maintenance is to run periodical check-ups and to fix when a failure occurs. However, any disruption to business continuity due to failure, incur heavier costs than the fix itself. The novel Industry 4.0 style solution for this issue is predictive maintenance, and it is only possible by constantly keeping an eye on the system states and the environmental parameters. Thus, digital twins play an important role in predictive maintenance as well, heavily contributing to the system resilience.

## Implementation

*How do you develop digital twins?*

The implementation of a digital twin begins with a careful planning of the aspects to be modeled. These aspects can be the different components of the physical system. For instance, the rotation speed of a wind turbine's blades and the status of lights in a smart house… These will determine the sensor requirements and the modality of the data which will be captured by those sensors. The aspects to be modeled are not necessarily limited to the internal components of the physical system. They may also cover environmental parameters via external sensors or data-providing services. For example, the weather forecasts of a wind turbine farm, or the outside temperature and sun exposure of the smart house…

Agile development approaches fit generally best to digital twin implementation projects. The implementation potentially requires a network of sensors, special hardware, precise visualizations, real-time communication, data integration and analysis, and rigorous testing. Therefore, handling such complex projects throughout many iterations leads to careful execution, managed risks, staged deployment, rapid testing, and an increased sense of ownership by the stakeholders.

## Challenges

*What are the challenges of implementing a digital twin?*

The implementation of digital twins inherits the challenges of any software-hardware development project. However, there are certain challenges that are characteristic for digital twins, for instance, building and maintaining the sensor network. To build a network of sensors, the individual sensors must be synchronized so that the data that they share can be mapped to one another. Most of the sensors also require periodical calibration. $CO_2$ sensors are a particularly good example, as without frequent calibration, they can make large measurement errors.

In many cases, a digital twin draws data from various sensors that are placed in the same system, yet the data differ in forms and ranges. A $CO_2$ sensor, for instance, measures the percentage of the $CO_2$ in the air and reports a continuous signal that ranges from 250ppm to 2500ppm under normal conditions. In the meanwhile, a motion sensor emits a discrete binary signal (e.g., movement/no-movement) whenever it detects movement. A digital twin of a smart house can use both data signals together to improve its occupancy detection capabilities. The challenge is to model the analytical process of the digital twin to handle multimodal data to achieve greater performance.

Often data about the modeled phenomena may not be available. In those situations, governing rules and heuristics can be used to build a simple model. In time, through interaction and feedback with the actual system, these rules can be improved and fine-tuned. Take the example of the digital twin of an airliner. The actual aircraft operates in a highly-complex environment. The dynamics of the air depend on many parameters, and these directly and continuously affect the state of the aircraft. While some of these parameters are accurately measurable or predictable (e.g., air temperature, wind-speed), some are very difficult to model (e.g., turbulence). While implementing such complex phenomenon, engineers rely on domain knowledge, formulas, and common sense. In time, the respective model of the digital twin can be improved and refined by accumulating and analyzing sensor data and feedback from the expert users.

Among many other challenges, the separation of actuated data and phenomenal data poses an interesting obstacle to overcome. This happens in cases which the digital twin is also used to control the physical system. The state-changes that occur due to the commands sent by the digital twin should be dealt separately from all other events that occur in the real system. Otherwise, the analytical models risk learning from their own actions, creating an unwanted feedback loop. Imagine a smart house which analyzes the occupant behavior and optimizes the energy consumption in the house based on this behavior. In that case, an inhabitant turning a light off is an example of user behavior, however, if it is the system that automatically turns the lights off, then it is actuation. To avoid inaccurate behavior modeling, the actuated data and phenomenal data must be processed separately.

## Use cases

*Which examples of digital twins are out there?*

Digital twin is a domain-independent technology. One can find the use of digital twins in large-scale dynamic and highly interactive systems (e.g., a smart city) or small-scale, stand-alone, isolated applications (e.g., a printer).

Factories utilize digital twins to monitor the manufacturing progress where the data comes in from each and every step in the process, from barcode scanners handled by workers to the system logs produced by robotic components.

Windfarms, solar panel fields, and offshore refineries are difficult to continuously monitor in a manual fashion. Digital twins allow the monitor and control of these systems with great ease. In extreme cases, such as the Mars Rover, the physical system is well beyond reach, however the digital twin makes it possible to still monitor the status of the system that is millions of kilometers away.

Digital twins can also represent chemical processes. They model the reactor environment and continuously sense the changes in parameters as the reaction occurs, allowing the discovery of optimal circumstances to engineer the desired outcome.

Analytical digital twins are transforming motorsports as well. A Formula 1 car embodies hundreds of sensors. The data coming from the sensors are collected, displayed, and analyzed on a digital twin that provides important insights for optimal performance during the race and valuable input to design improvements afterward.

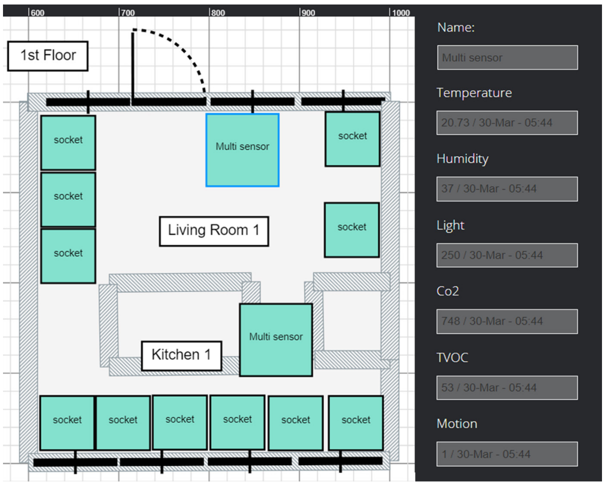


*Figure 1-The digital twin of the Digipro smart house*

Equipped with a variety of sensors, smart homes (or offices) keep a close eye on the inhabitant behavior, ensure a healthy and comfortable living environment, and also enable significant savings on energy consumption. A digital twin makes that information available to the inhabitants and provide an easy way to control different components of the house (Figure-1).

In a smart city, digital twins can take many different types of inputs from the sensors around the city such as traffic lights, energy consumption, air quality, and environmental noise, and also from the actors of the system, such as the public transportation vehicles and service units. In a comprehensive smart city, every citizen is a potential sensor. They might provide real-time information which is otherwise unavailable, and a digital twin makes this huge network of data accessible and usable.

## Actionable Conclusion

- Think about digital twins as a virtual representation of any system.
- Due to certain technological trends over the couple of years, digital twins have gained a lot of attention. However, the underlying technologies have been around for decades.
- A digital twin does more than visually representing the current state of the physical counterpart. It can also show the past state-changes, and predict which states the actual system will arrive in the future.
- Digital twins make it possible to monitor and control physical systems remotely, highlight process bottlenecks and identify optimization opportunities, and provide patterns of data that enables predictive maintenance. Digital twins can be used in the training of personnel who need to interact with the physical system.
- There are certain challenges in the implementation of digital twins. Knowing how to handle them in advance will increase the chances of a successful project.
- Digital twins are domain-independent. It is highly likely that you will find a use case in your domain of operation.

## Contact

*Have questions or comments?*


**Dr. Deniz Iren, PMP**
Assistant Professor
Center for Actionable Research of Open University
Department of Information Sciences, OU
deniz.iren@ou.nl