Journal Title
XX(X):1–3
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DOI: 10.1177/ToBeAssigned
www.sagepub.com/
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Beyond Digital Twins – A Commentary

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Keywords
Digital twins, building information models, smart cities, cyber-physical-social systems, simulation

In his editorial of Issue 5 this year Michael Batty critically reviewed the term 'digital twins', calling it a cliché (Batty 2018). We concur with his arguments that this fashionable term is plagued by a variety of interpretations, some of them even misleading, i.e., when defined as a 'replica', or a 'mirror' of a physical object or system (Grieves 2014, referring back to 2003). We also point out that the metaphor of a 'twin' is axiomatically ill-conceived when referring to a replica or a mirror image. But apart from that, Batty argues that "in general, a computer model of a physical system can never be the basis of a digital twin [i.e., 'mirror'] for many elements of the real system are ignored in any such abstraction" (Batty 2018, p. 817). Yet, Batty himself states at the end of his editorial that "the idea of moving a digital model closer and closer to the real thing is in fact a basic rationale for building computer models" (Batty 2018, p. 819), thus arguing that the idea of a 'digital twin' is relevant. In our commentary we are investigating what this is that should be retained as relevant, and conclude that the metaphor of a 'digital twin' should be replaced. What is emerging in this investigation is better characterized as a cyber-physical-social system with coupled properties. The coupling of the physical with the digital has properties of an organism. It is capable not only of reaction and prediction, but increasingly also of action (rather than being the passive reflection of a mirror). The coupling also implies that the system to describe is not a purely digital one. Hence, more appropriate metaphors for are found in the role of brains in organisms.

Of the coupled properties of an organism we want to highlight three: (a) it can sense the (physical or digital) environment and updates its counterpart accordingly, (b) it has agency and can change the (physical or digital) environment based on instructions, possibly from the counterpart environment and including engagement with people, and (c) it has a moderation system that attempts to preserve its operational inner state, here called an immune system.

What is relevant about 'digital twins'

The term 'digital twin', originally used with respect to manufactured artifacts (Grieves 2014) recently made inroads in the geographic information community, propelled by technical developments closing the gap between the physical environment and their digital representations. Here, it joined current fashionable buzzwords such as the *Internet of Things* (Kopetz 2011; Wortmann and Flüchter 2015) and *Cities 4.0**. The term 'digital twin' has been applied to representations of buildings and aggregations thereof such as precincts or entire cities – as long as these representations preserved aspects of temporal dynamics and self-updating ('4D'). This self-updating property should make these representations, metaphorically, 'mirrors'. If the representations are imbued with agency, they even become counterparts. This is how far the metaphor of 'twins' goes.

Let us consider the 'twin' as a representation that resembles (rather than mirrors) certain desired behaviours of the physical artifact *faithfully enough*. In true 'twinness' the 'twin' comes into existence synchronously with the artifact it resembles (or with low latency, as Batty points out) and it also ceases existence when the artifact ceases to exist. The properties of the 'twin' are also updated synchronously with changes to the physical artifact *and vice versa*.

Sensing

For digital representations that rely on sensing, the notion of scale is superseded by the central notion of resolution, and resolution implies sampling from a domain: The *spatial* resolution depends on the distribution of sensors in space, and the *temporal* resolution depends on the sampling frequency of the sensors. A challenge for the digital representation that relies on sensing is the integration of sensor readings that come at different spatial and temporal resolutions.

The sampled readings from sensors determine the faithfulness of the 'digital twin's' representation of an environment. The type of sensors, their capabilities (resolution, frequency and accuracy) and their density and placement determine the detail of the representation (Nyquist 1928). System engineers design a 'digital twin'

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* https://www.youtube.com/watch?v=KWAVgyG3lvE

for a particular purpose, with appropriate level of detail. Analyzing a well designed 'digital twin' environment then leads to results sufficiently similar to observing the physical environment.

The dependency on sensing reveals an important property of what has been called 'digital twins': they rely on continuing supply of energy and information, as does any physical body. The loss of electrical power leads to termination of the 'digital twin' – in contrast to a persistently stored database, information model, or stored result of a simulation. 'Digital twins' thus have very specific transactional characteristics compared to other information models (Härder and Reuter 1983) – they cannot simply be turned off and on again, as much as the represented physical world cannot be turned off and on again. Interactions and changes in the physical environment would be lost, as there is no meaningful buffering of transactions. The digital representation, should it reboot after power failure, would no longer be a twin. Such rebooting is not permitted as it could lead to inconsistent representations of the physical environment in the digital counterpart.

Sensing, representing and reasoning in near-real-time processes require sensing and communication infrastructure (Xia et al. 2012; Wortmann and Flüchter 2015). This hardware and software infrastructure of the 'digital twins' is part of the physical reality and can be compared to the senses and nerve system (including the brain) of an organism, along with all interdependencies. As a result, the 'digital twin' is embodied and immersed in what it is supposed to mirror, and thus is no longer an independent representation.

Similar to organisms, these coupled physical and digital systems, where the digital part has been called 'digital twin', can integrate into societies (i.e., it is not only the 'twins' that form these societies). Societies consist of multiple, topologically connected peers interacting together. For example, all the buildings of a university campus, together with their digital representations, integrate in a society that forms the coupled physical and digital system of the campus. Here, the aggregated digital system is likely to be richer than the sum of the 'digital twins' of the buildings, with emergent complex behaviours and dependencies.

Such societies of 'digital twins' are mutually consistent. As a consequence, traditionally hard problems such as map generalization are no longer meaningful or at least not directly applicable. Operations such as selection, simplification, and displacement lose meaning when the consistency of the 'digital twin society' needs to be maintained. Yet, interpolation and extrapolation remain meaningful. Hierarchies of peer twins, or across types, may form in these societies, such as the aggregations from smart rooms through buildings and precincts to smart cities. These hierarchies may dynamically reconfigure based on needs.

The emergent complex systems are known to be intrinsically difficult to model due to the exploding number of behaviours enabled by the re-configurations of the 'twins', their relationships and individual behaviours.

Agency

A physical environment already interacts with people: by its design it supports certain uses and functions through affordances (Norman 1988; Gibson 1979), and by mechanisms such as signage or traffic lights or by design it asserts certain primitive control (Jonietz and Kiefer 2017). The digital side of a coupled system, however, can react, predict, and act. It can control the traffic lights according to traffic, guide by digital signage, and provide information about the physical environment on request, *in* the environment or in the hands of people, enabling interaction. This means the digital side of the coupled systems (the 'digital twin') morphs into the physical environment by communication and control, a phenomenon studied by cybernetics (Wiener 1948).

Batty observed that 'digital twins', as representations of a physical environment, cannot be used to investigate alternative environments, or simulations of futures of this environment, because then they would per definition be no longer representing the current environment (Batty 2018). The embodied, immersed sensing, and acting of a coupled physical and digital system, however, can very well have a capacity to produce and represent alternative states of itself – in the same way a brain of an organism is able to produce alternative states out of its learned images (Damasio 2010). A digital system uses an image snapshot of the the current or past representations, together with its ability to predict by extrapolation. Such simulations can be part of an active control strategy, but can also be made in interaction with humans who are investigating alternative states of the environment, alternative responses to changing conditions in the environment, or extrapolated future states in the environment.

Immune system

With the emergence of this tight, bi-directional coupling between the physical artifact an their digital counterpart, let us carefully examine what the health of the coupled ecosystem entails, and how would a moderation system preserving its health look.

Physical artifacts are prone to malfunction and failure. Indeed, one of the primary reasons for the development of the digital counterparts of such artifacts was to monitor the health of the physical infrastructure. Critical engineering infrastructure (electric transmission networks, water distribution, railways) equipped with sensors and actuators have arguably been among the first digital coupled ecosystems, where the term 'twin' has been used. Yet, we can no longer rely on the digital system being less error prone, or more robust than the physical environment. The cybersecurity community is now increasingly concerned with the vulnerabilities of the digital control systems on the operations of the physical infrastructure such as traffic lights (Ghena et al. 2014). But vulnerability of both the physical and the digital system calls to treat the coupled system as a single 'body', and investigate its vulnerabilities as well as mitigation strategies in a unified approach. We call it, metaphorically, an 'immune system'. This system must protect 'digital twins' from attacks in the physical environment (i.e., tampering with sensors, disconnecting communication lines), as well as from cyberattacks (denial of service attacks, overriding of control mechanisms). Similarly to the innate immune responses that are available to a human, increasingly sophisticated methods learning from the operation of the system itself or from its peers (through 'inoculation') may need to be devised. Artificial immune systems have already been investigated Dasgupta (2006).

Conclusion

This commentary observes, in agreement with Batty, that the metaphor of a 'digital twin' falls short in multiple ways. But it lines out the research vision inspired by the metaphor, along three critical characteristics of sensing, agency, and an immune system. We also demonstrate that these characteristics require a tightly coupled physical and digital system showing certain analogies to living bodies, rather than a separate 'digital twin'.

We argue that the coupling even includes people in the represented environment (and outside). A *cyber-physical-social eco-system* relates to an organism with a brain: the digital counterpart is coupled with the physical realm (*cyber-physical*) by a nerve system of sensors, actuators, and (information-processing) communication lines enabling agency, and the digital representation interacts with people (*cyber-social*) through the physical environment including physical communication devices such as screens, enabling also the investigation of alternative physical systems.

The brain of a living being tightly maintains a memory (representation) of the body itself, and only secondary of the outside world (Damasio 2010; Riva 2018). This brain reaches out through a skeleton of nerves, and considers and reacts to perceptual stimulus. It maintains a representation of the state of the body that is capable to focus attention. All these properties are desirable for the representation so far labelled as 'digital twin', and thus better labelled the 'brain' of a body – so far, without claiming consciousness.

Acknowledgements

The researchers acknowledge support by the Australian Research Council, DP170100109 and DP170100153.

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