Security-Enhancing Digital Twins: Characteristics, Indicators, and Future Perspectives

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Abstract—The term "digital twin" (DT) has become a key theme of the cyber-physical systems (CPSs) area, while remaining vaguely defined as a virtual replica of an entity. This article identifies DT characteristics essential for enhancing CPS security and discusses indicators to evaluate them.

■ **DIGITAL TWINS** are considered to be a key enabler for future industrial automation technologies. Driven by Industry 4.0 and "Factory of the Future" initiatives, digital twins (DTs) have evolved from highly specialized aerospace applications to a wide variety of domains, including manufacturing, energy, and transportation.

The interpretation of the DT concept varies among researchers [1]: some understand it as a digital representation based on a data-driven solution or simulation; others consider it to be a composition of physical models of interdependent components that use input data from the real world to reflect the system's current state or forecast its future behavior. In the past few years, numerous DT applications have appeared in literature, some of which were even further developed and released as a product for market use. Examples of how DTs are currently applied in practice include: machine learning models, asset-related data objects (à la asset administration shell), backends for IoT devices (e.g., Eclipse Ditto), virtual testing solutions, and detection algorithms for abnormalities (as presented, for instance, by Jiang et al. [2]). While recent surveys on the state of DT research and technology adoption (e.g., [1], [3], [4]) attempt to consolidate existing definitions and clarify the characteristics of DTs, they do not consider the use of this concept for security applications.

The capabilities promised by existing implementations of the DT concept raise the question of how such virtual replicas of cyber-physical systems (CPSs) can also be used for securityenhancing purposes. The absence of a classification system makes it difficult to recognize the potential of security-enhancing digital twins (SEDTs) and to compare with existing solution proposals, especially if "digital twin" is used as an umbrella term for various CPS-focused security mechanisms. This gap in the literature hinders progress, as misinterpretation may arise if the proposed SEDT solutions do not clearly state the key characteristics and advantages compared to existing security concepts. Moreover, a consistent vocabulary and common view on the components cannot be established without a systematic classification of characteristics. Overall, the current body of research gives rise to the following questions:

- What are the promised advantages of SEDTs for improving the security of CPSs?
- How do SEDTs differ from established security concepts and approaches?
- What are the characteristics of SEDTs and

1

how can they be evaluated?

• What are the current challenges and barriers faced by the CPS security community when developing SEDTs?

The remainder of this article addresses each of the above questions to provide a source of reference for future research on SEDTs.

Glossary of Terms & Related Concepts

Cyber-physical system (CPS): A CPS employs computing elements and interacts with the real world by means of sensors and actuators.

Cyber range: A cyber range is a security testbed used for training and testing purposes.

Data-driven model: A data-driven model is derived from previously collected data samples, for example, by using machine learning methods.

Deception technology: Deception technologies, such as honeypots, are systems set up as decoys to detect and study cyberattacks.

Emulation: An emulation mimics the inner workings of a system with the objective of substituting it in some analysis or test scenario.

Hardware-in-the-loop (HIL): A HIL test setup consists of the real hardware of the embedded system under test and a simulated environment featuring the dynamics of the studied CPS.

Physical model: A physical model (often also referred to as a plant model) is a mathematical representation of physical system behavior.

Simulation: A simulation models the behavior of a system or phenomenon for analysis purposes.

Software-in-the-loop (SIL): A SIL setup enables the testing of embedded software under simulated conditions as generated by the plant model.

Promised Advantages of SEDTs

Fig. 1 illustrates potential elements of a DT and its physical counterpart using the example of an industrial mixing system, which is part of an industrial control system (ICS) employed at a chemical production site. As shown, a DT can be implemented by means of simulations, emulations, and data-driven models or a combination thereof. Since the concrete implementation of the DT depends on the use case of interest, Fig. 1 displays merely a collection of components that may appear in some form or another.

SEDTs that are specifically designed to improve CPS security have various applications that boil down to one overarching benefit: they allow users to gain a deeper understanding of the past, present, or future system behavior without the risk of causing operational disruption or physical damage.

Security Use Cases of SEDTs

In the following, we briefly describe those cybersecurity application areas where we consider that the usage of an SEDT yields the greatest benefit in the context of CPS security.

Security Analysis and Risk Assessment. SEDTs can benefit security analyses, as attack scenarios (including potential cascading and mutually amplifying effects) can be explored without affecting the normal operation of the real system. As such, they enable users to explore hypothetical scenarios featuring threats and countermeasures on the virtual network, system, and application layers, while the resulting negative and positive effects can be observed on the field level via the integrated physics-based or data-driven model(s). Moreover, an SEDT can assist in estimating the loss probability by determining the attacker's success paths. It can also be used to expose experts and decision makers to worst-case scenarios when forming their judgments on loss severity.

Security Testing and Certification. An SEDT, which includes relevant security mechanisms of a real system and can emulate behavior under real attacks, allows security analysts to routinely perform penetration testing and other forms of security testing without affecting the real systems. Furthermore, such SEDTs might be used to support security- and safety-related certification activities by acting as a surrogate to demonstrate the CPS's robustness against adverse events.

Training. Using SEDTs for training might offer flexibility and a sufficient level of realism, possibly making security exercises more effective and rewarding for the trainee. SEDTs have the added benefit of showing trainees the direct effects of security controls on a virtual representation of the system under consideration (e.g., via full system and network emulation).

Forensics. SEDTs offer the ability to analyze events without the risk of tampering with the real systems and available evidence [5]. Furthermore, they provide a wealth of information (e.g., trace data, execution history, states of the physical system) to support forensic analysis and allow for preserving systems beyond their lifetime. As

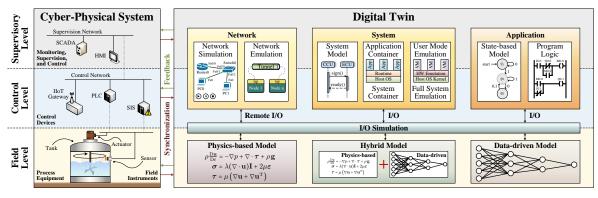


Figure 1. Schematic structure of an automated industrial mixing process as an example of a CPS and its corresponding DT. Note: A concrete DT implementation may comprise a mix of the elements presented (depending on the security use case of interest) and the labels used in the illustration only indicate the general scope (e.g., control logic, SCADA software, and HMI software are all subsumed under "program logic"). Furthermore, real systems and peripheral devices may also be connected to the DT to address certain constraints such as emulator limitations.

a result, an incident could be discovered and investigated (with limitations) after the system has been modified (or even decommissioned).

Intrusion Detection. Comparing the behavior of an SEDT with that of its physical counterpart further opens up the possibility of detecting intrusions. Behavior-specification-based intrusion detection systems (IDSs) rest upon a formal specification of legitimate behavior, which typically requires significant effort to create [6]. An SEDT, which is an instantiation of a specification, does not ease this burden, especially since its scope is extended to cover the network, system, logic, and physics layers. However, the multi-layered feature of an SEDT yields more audit material than existing IDSs of this class, which typically collect either host-based or network-based data. In the context of behavior-based intrusion detection, SEDTs can also be used for data generation purposes as an alternative to gathering data from the real CPS. This will not only provide greater flexibility in data acquisition but also ensure that potential intrusions are not already present in the training data (in case supervised learning is applied). SEDTs can also illustrate anomalous behavior by reacting to simulated cyberattacks and common system faults to complement data reflecting normal behavior.

Response. Once an intrusion has been detected, SEDTs can help to perform root-cause analysis and support the planning of a reactive response in order to minimize the attack impact and recover from the effects of a compromise. This can be achieved by simulating similar threats against SEDTs and testing possible countermeasures to assess their effectiveness as well as their effects on the physical process.

Deception. The components developed in the course of SEDT creation might be reused to run a honeypot alongside other systems as part of the real CPS. Since an SEDT is normally designed to closely replicate the behavior of its physical counterpart, its application as a honeypot could yield a high level of interaction and realism.

Patch Management. SEDTs can support patch management by providing the means to test patches on virtual replicas without disrupting or endangering real systems [7].

Key Differences from Existing Security Approaches

The previously described security applications of SEDTs are inspired by existing concepts that are backed by an extensive body of research. This naturally raises the question of what unique aspects are actually offered by SEDTs. We therefore highlight the anticipated capabilities of SEDTs in comparison to established security approaches.

Security Testbeds and Cyber Ranges. SEDTs, as purely software-based solutions, provide a cost-efficient alternative to cyber ranges that integrate physical elements, provided that proper tools to generate and operate them are available.

Specifically, the procurement and provisioning for hardware-based environments typically entail considerable costs. Furthermore, even after rampup, (semi-)physical testbeds demand manual effort to manage devices (e.g., modify setups, tear down after test execution). Uncontrolled failures may also lead to damaged equipment, incurring additional expenses.

Software-in-the-loop (SIL). We view the SEDT as a more capable solution that goes beyond functional testing of a CPS as it provides the means to study the behavior of the system under unintended adverse conditions while considering feedback from the real-world environment.

Security Modeling Tools. SEDTs may transform the fragmented security solution landscape, which is characterized by information silos that emerged with the proliferation of individual, custom-built (sub-)models for security analysis. The assessment scope of security analysis tools is typically limited to specific parts of the CPS, and the employed information models are often stored in proprietary formats, leading to isolated consideration of security aspects. The SEDT, as a unified virtual representation of the CPS, connects multiple models to support security analyses from different perspectives. This advantageous trait also enables "security by design" for CPSs: an SEDT can exist already in the early phases of the CPS lifecycle, even before the real system is built, and thereby inform engineers about security-relevant issues. As the CPS evolves throughout its lifecycle, the SEDT functions as a digital companion to support continuous security upgrades.

Data-Driven Models. It is worth noting that the DT, in general, is often understood as a datadriven model constructed with data collected from real-world objects [1], [4]. In contrast to this position, we adopt the "classical" perspective of the DT concept, which does not restrict DTs to pure data-driven models but rather embraces an integrated approach that combines them with physicsbased models and system models (as originally envisaged by NASA [8]). While SEDTs certainly build upon historical and real-time data coming from the CPS, their method of construction is typically not limited to machine learning algorithms and may also include system emulation, network simulation/emulation, models of control logic, and physics-based models (cf. Fig. 1).

Deception Technology. When SEDTs are specifically designed to function as a form of deception, there will be a high degree of technological overlap with high-interactive honeypot systems, as the SEDTs should be barely distinguishable from real systems in order to deceive attackers. One advantage of SEDTs is that they may facilitate the combination of deception and moving target defense (MTD) approaches by supporting dynamic changes to the virtual environment, aiming to interfere with the attacker's efforts to identify decoys. However, an SEDT used as a decoy should not have a bidirectional connection (or unidirectional connection $DT \rightarrow CPS$) to avoid any negative "spillover" from an attack. Moreover, precaution must be taken when using SEDTs as decoys since they may disclose valuable information about the actual systems.

Characteristics of SEDTs

Existing scholarly and professional publications on the characteristics of DTs lack a thorough consideration of the requirements needed to implement security-enhancing use cases. To address this gap, we have co-organized a Dagstuhl seminar [9] on DTs for CPS Security. The taxonomy presented in Figure 2 was derived through workshop-style discussions on the requirements of the described security-related purposes in addition to a systematic analysis of the general characteristics of DTs (e.g., [4], [3], [10]). The introduced taxonomy describes the characteristics of SEDTs in a structured manner and enables the classification of future DT-based security solution proposals. Based on this, we offer suggestions for qualitative and quantitative indicators to evaluate the proposed characteristics, aiming to provide a starting point for a fair comparison among SEDT solutions.

Fidelity [C1]–[C8]

The term *fidelity* is loosely used in the modeling and simulation community to refer to the "level of detail" of a simulation, yet a widely agreed and clear definition is missing [11]. In the context of SEDTs, the understanding of this term is correspondingly vague: the fidelity of an SEDT refers to how closely it resembles its physical counterpart. We argue that the lack of clarity about fidelity hampers the adoption of the DT concept, as misunderstandings may already arise during requirements engineering and propagate to subsequent phases. Furthermore, this obscure definition inhibits the measurement of fidelity, which is necessary to assess the suitability for purpose [11]. To narrow the room for interpretation, Roza et al. [12] proposed fidelity concepts that decompose the notion of fidelity into more concrete elements, and thereby provide a clearer sense of this term.

Before we introduce our notion of DT fidelity, we want to direct the reader's attention to the following important issues raised by Roza et al. [12]: First, fidelity is measured by comparing the virtual replica to the perceived real-world counterpart. Naturally, the perception of reality is incomplete at best and flawed at worst. Second, comparing observable properties of the real system can only be indicative of how well the data points are replicated (by the DT), not how well the actual behavior is reflected. Third, such virtual replicas may be employed at a stage where the real system is still in development or completely non-existent, making data collection for fidelity measurement infeasible. Roza et al. [12] addressed these issues by introducing the concept of a *fidelity referent*, which can be understood as a description of knowledge that approximates reality. Such specifications offer a pragmatic basis for fidelity measurement.

In the following, we build upon the fidelity concepts of Roza et al. [12] and adapt them to the context of DTs (and, more specifically, SEDTs): **Model Resolution [C1–C2]** comprises the completeness and abstraction level of the SEDT.

Completeness [C1] is a measure of how exhaustive in breadth the CPS is virtually replicated. In the system-of-systems context, this characteristic indicates the extent of the CPS for which SEDTs exist. For instance, in an isolated view that is strictly limited to computer systems, a complete SEDT of an ICS would be composed of a set of SEDTs, where each member corresponds to one system employed as part of the real ICS. Due to the physical dimension, defining full completeness, let alone achieving it, is infeasible. Nevertheless, the completeness of an SEDT (also taking the physical system into account) can be evaluated with respect to a referent that specifies the physical properties that would have

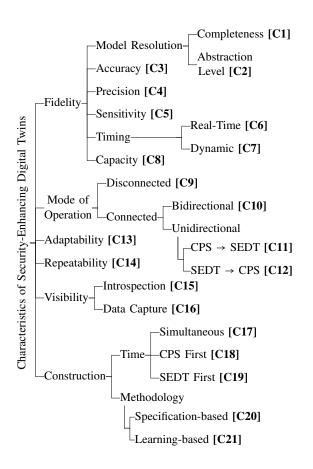


Figure 2. Characteristics of security-enhancing digital twins.

to be modeled for achieving the desired security purpose.

The degree of abstraction of an SEDT [C2] is influenced by its "depth" (i.e., detail). The spectrum of abstraction relates to several levels in which CPSs function. On the computer system level, this may take the form of a simulated model of computation (e.g., Petri net), a simulated system model (e.g., based on a SysML model), or full system emulation (e.g., via QEMU). Similarly, on the network level, simulating communication networks will yield a higher degree of abstraction than fully emulating the network stack. Opting for reduced computational complexity in lieu of lower abstraction by employing a reduced-order model as an approximation to the full-order model is an example for the physical level.

Relevance to Security Use Cases. The required completeness [C1] of the SEDT primarily depends upon the purpose and scope of the security

use case(s), which determine the computer systems, physical processes, network infrastructure, etc. that need to be covered.

Similarly, the requirements relating to the abstraction level [C2] strongly depend on the chosen security use case, as well as the scope and purpose of evaluation. For instance, determining attack scenarios and assessing their effects may not require a low level of abstraction since attack simulations on system models are presumably sufficient to understand potential attack paths and consequences. On the other hand, conducting threat hunting or investigating the attack paths in play during an incident in order to find the next pivot action that is likely to be taken by adversaries will necessitate a more detailed emulation of systems. In addition, SEDTs deployed as decoys must provide a high level of interaction, which is governed by the degree of abstraction, in order to avoid identification as honeypots. However, low abstraction may not necessarily imply equivalent utility across all security use cases. For example, an SEDT with low abstraction used as a basis for an IDS may not directly lead to increased detection performance. The reason for this is that less detail (i.e., higher abstraction level) may result in greater robustness in terms of sensitivity and fewer synchronization errors.

Indicator Considerations. Completeness [C1] can be measured as the proportion of the covered CPS components and physical properties of the real systems, which are required for the intended security purpose. On the other hand, the abstraction level [C2] can be measured by gauging which details have been left out (or generalized) with respect to a referent.

Exemplary Sources. Suggested sources for creating a referent are engineering artifacts detailing the plant topology (i.e., structure of system resources and communication networks) to cover the digital elements of the CPS, whereas information about the physical part can be obtained from the specification of theoretical knowledge about the physical phenomenon and empirical data collected from the physical system.

Accuracy [C3] describes how close an observed property of an SEDT is to the observed property of the real system (or the *true* value, if it is known). An SEDT with high accuracy would produce the same outputs as the CPS when presented with the same inputs and environmental conditions. If accuracy decreases below a certain threshold, the SEDT may not be considered a twin anymore.

Relevance to Security Use Cases. Using an SEDT as a form of deception is the only security purpose where accuracy can be sacrificed for practicality. High levels of accuracy are a must-have requirement for the other security application areas, where defenders consuming the outputs produced by SEDT heavily rely on the accuracy of results to make well-informed decisions. For example, the IDS performance (i.e., measured in terms of false positive/negative rates) is heavily influenced by the accuracy of the underlying SEDT.

Indicator Considerations. Accuracy can be expressed in quantitative terms using classical error measures, such as absolute error and relative error.

Exemplary Sources. A referent may be sourced from empirical knowledge or from subject matter experts who specify referent data points.

Precision [C4] refers to the degree of exactness, in terms of the resolution or granularity of representation, of the outputs or results produced by an SEDT. The concrete manifestation of precision depends on the type and format of the considered output values. In the most basic case, this can be the arithmetic precision of a numeric value. Limited precision may be caused by the SEDT's level of abstraction, inherent shortcomings of its implementation, or even deliberately accepted with the intention of increasing efficiency. For instance, round-off errors are a natural consequence of finite arithmetic applied in numerical computation, whereas simplifications in mathematical calculations are made to improve the performance, possibly at the cost of lower precision.

Relevance to Security Use Cases. Low-precision computation can have negative effects on the accuracy of the SEDT. In particular, less precise output values may introduce or amplify errors along the SEDT execution path, undermining the utility of analysis outcomes. However, for certain use cases (e.g., deception), the resulting accuracy drop may be acceptable.

Indicator Considerations. In numerical analysis, a quantitative indicator of precision is given by the total number of significant digits. For non-

numeric outputs, qualitative indicators can be established and checked against referent knowledge. For example, consider precision as it pertains to network communication: simulating every individual network packet would yield higher granularity than flow-level simulation—yet at the cost of greater computational effort.

Exemplary Sources. The precision of the CPS's computer systems can serve as a baseline for the corresponding models used as part of the SEDTs. Approximating physics necessitates careful consideration of various parameters, such as modeling approach, phenomena to be studied, and computing environment.

Sensitivity [C5] indicates how an SEDT's behavior is affected by internal or external input inaccuracies. High sensitivity can negatively affect the execution of SEDTs in all modes of operation. Normally, the SEDT setup consists of multiple instances that interact with each other; hence, output errors may propagate in an uncontrolled way and accumulate throughout the execution process. Furthermore, additional sources of error can emerge when SEDTs are synchronized with their physical counterparts, as the real-world data is often noisy and may be incomplete.

Relevance to Security Use Cases. Sensitivity has a direct influence on those security use cases where interaction among SEDTs exists (e.g., via I/Os) or SEDTs are synchronized with their corresponding real systems.

Indicator Considerations. Sensitivity can be studied in a standalone setting or with respect to the CPS (or referent). In the former case, general practices can be borrowed from the field of sensitivity analysis, whereas indicators of the latter category are obtained by measuring the error in output values in terms of the deviation from the benign, real system in different modes of operation (e.g., accumulated error through the execution of one or multiple SEDTs).

Exemplary Sources. The input/output behavior of the CPS, provided that it exists and proper test conditions can be established, may serve as a primary source for the specification of relevant referent knowledge.

Timing [C6]–[C7] expresses how the state of an SEDT advances in relation to its physical counterpart. This characteristic can be further subdivided into timing configurations of SEDTs, viz., real-time and dynamic. To run an SEDT synchronous to the corresponding real system, real-time support [C6] is required, meaning that it is executed in discrete time with a constant step size sufficiently approximating the continuous behavior of the physical counterpart. In order to achieve this, the SEDT should advance at least at the same rate as the computationally-enabled components of the CPS. The possibility to (dynamically) accelerate or decelerate the execution of the SEDT [C7] can also be important for certain use cases, such as predictive analysis.

Relevance to Security Use Cases. As indicated above, real-time support is mandatory for those security use cases that require the SEDT to be synchronized with its counterpart (e.g., intrusion detection, forensics) or if it must perform at the same rate as the actual system (e.g., security testing, training, deception, patch management). The support of dynamic temporal resolution, on the other hand, may enable a forward-looking perspective on how the state of the corresponding system might evolve over time after a certain activity has been performed (e.g., implementation of countermeasures to respond to a detected intrusion).

Indicator Considerations. The real-time characteristic [C6] of an SEDT can be classified and measured in the same way as real-time systems. Timing analysis may be conducted to assess, inter alia, latency and jitter, aiming to determine if it can be guaranteed that deadlines are met. Indicators for dynamic timing [C7] can be both qualitative and quantitative:

- <u>Feature-wise</u>, to describe key qualities of the functionality provided (e.g., time resolution and speed adjustments, single stepping, conditional breakpoints).
- Accuracy-wise, as a proxy measure, to determine how accurate the results of the execution with variable control over steps are.

Exemplary Sources. Information for the referent may come from specified time requirements with respect to the task execution of control devices being used in the CPS (e.g., cycle times, jitter tolerance).

Capacity [C8] relates to the performance of an SEDT implementation. This characteristic is influenced by the hardware and software used to run SEDTs and dictates, for example, the number of instances that can be executed on a given node at the same time.

Relevance to Security Use Cases. As is the case with completeness [C1], capacity requirements are mainly driven by the security use case of interest and the CPS at hand (e.g., runtime overhead caused by virtually replicating the control level and field level).

Indicator Considerations. Capacity can be determined by measuring the performance of the (hard- and) software components of the SEDT implementation. Analyzing algorithmic efficiency and virtualization overhead are two examples of how this characteristic can be assessed.

Mode of Operation [C9]-[C12]

We distinguish between different modes of operation based on the communication between the CPS and SEDTs.

Disconnected [C9]: As the name implies, no data flow exists between the physical (i.e., real-world) environment and the virtual environment. This mode essentially resembles the conventional runtime options of simulations (batch or interactive), where SEDTs are executed with a set of initial parameter settings and run independently of their physical counterparts. Thus, state changes of the real system are not reflected in the corresponding SEDT.

Relevance to Security Use Cases. For certain use cases, such as security testing or training, it may be mandatory that the SEDT is disconnected from the real system to avoid any accidental disturbance; yet, it may still be beneficial to initialize the SEDT with a state previously observed in the real world to create a suitable test or training environment.

Connected [C10]–[C12]: A physical entity can be linked to its digital twin via a unidirectional [C11]–[C12] or even bidirectional [C10] connection. The unidirectional category can be further subdivided into two groups on the basis of where data flows originate.

Data flows originating from the real-world environment [C11] (or [C10]) are used to synchronize the SEDT with its physical counterpart, ensuring that it replicates the current state with a certain delay. Such synchronization is implemented by means of a state replication mecha-

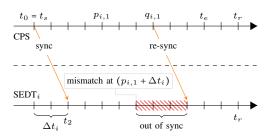


Figure 3. Example of a synchronization session (assuming a discrete approximation of time, where $T = \{0, ..., r\}$ and $t_k \in T$). SEDT_i is synchronized over the time span t_s to t_e and follows the states of the respective real system, which is part of a CPS, with delay $\Delta t_i = 2$ time intervals. The synchronization session starts at t_0 and ends at t_{10} , with one outof-sync region in between (3 time intervals). p_{ij} and q_{ij} are the start and end of SEDT_i being out of sync (relative to the time scale of the CPS).

nism that collects data from the CPS either in a passive [13] (e.g., network traces, system logs, measurements of the plant's output) or active manner [14] (e.g., polling). Note that running SEDTs in this mode does not necessarily mean that the state representation within SEDTs must *exactly* match the one of the real systems since they might combine several states into one abstract state. Furthermore, state replication mechanisms can be categorized according to the scope of synchronization, viz., partial sync and full sync (i.e., selective synchronization of some SEDTs or all of them). Fig. 3 visualizes the core ideas of SEDT synchronization.

An SEDT may also have a direct data link to its physical counterpart [C12] (or [C10]) to implement a feedback mechanism. For instance, if the evaluated (reactive) strategy to counter current threats has the desired effect on the SEDT, the re-configurations and countermeasures applied in the virtual environment can be carried over to the CPS. In a similar vein, proactive responses can be initiated when new security weaknesses have been revealed, even if the CPS is already in operation. We recognize that different tiers of backflow to the CPS exist, which indicate the achieved level of automation in terms of how the CPS uses this feedback.

Relevance to Security Use Cases. A connection between the CPS and the SEDT is required in one of the following cases: (i) to base the intended

security measure implemented by means of an SEDT on a current state of the CPS (e.g., security analysis, forensics, intrusion detection); (ii) to directly transfer the changes previously tested on an SEDT to the respective real system (e.g., rolling out recovery procedures).

Indicator Considerations. The performance of state replication methods can be quantitatively assessed in various ways: For instance, by calculating the mean time between state mismatches (higher is better) and mean state replication delay across all synchronized SEDTs (lower is better). In addition to these quantitative indicators, we suggest qualifiers to describe the degree of autonomy achieved when an SEDT provides input to the CPS:

- <u>Manual.</u> The results obtained from the SEDT are only for human consumption and require a manual process to make use of them (e.g., IDS alerts users upon detection of malicious activity).
- <u>Cooperative</u>. The SEDT automatically suggests (tested) changes but depends on human interaction (e.g., manual approval) to deploy them to the production environment.
- <u>Autonomous.</u> No human intervention is required at this level, as the SEDT identifies, tests, and fixes issues autonomously such that the CPS can fully adapt to the dynamic environment.

Adaptability [C13]

This characteristic refers to the possibility of changing components and configurations of the SEDT. For instance, potential changes to the SEDT may relate to the peripherals of the emulated system, network configuration, and simulation parameters.

Relevance to Security Use Cases. An SEDT with adaptability capabilities could facilitate security analysis, security testing, and training by enabling quick iterations with continuous configuration changes, thereby fostering frequent feedback.

Indicator Considerations. Qualitative indicators can be established on different levels: (i) industrial domain level (e.g., an SEDT originally employed for a wastewater treatment system is reconfigurable to also support natural gas power plants), (ii) CPS architecture level (e.g., adaptations of SEDTs in a system-of-systems context), (iii) component level (e.g., parameters and structure of the models employed in an SEDT), (iv) runtime level (e.g., modes of operation), (v) construction level (how the SEDT evolves with respect to the lifecycle of the CPS), and (vi) feedback level (e.g., static or dynamic reconfiguration of SEDTs after test cases failed).

Repeatability [C14]

Two identical SEDTs that receive equivalent external inputs should produce equal states and outputs, given the same initial conditions. This key property ensures that resetting an SEDT to a previous (known) state is reasonable. For instance, users might want to save and return to a specific point in time in order to repeat a scenario or to try a different investigation procedure from the same starting point. To do this, the ability to create snapshots (i.e., capture the history of states of a system at a point in time) is critical. It follows that non-deterministic behavior in simulations integrated into an SEDT inhibits repeatability.

Relevance to Security Use Cases. Repeatability is essential in cases where the results of multiple SEDT runs must be comparable. Exploring alternative scenarios with the same SEDT, restoring past states to repeat tests, and providing a controlled setup to compare the consequences of deployed patches are a few examples of security purposes where repeatability is strictly required. *Indicator Considerations.* An indicator for repeatability is obtained by measuring how close a result gained through an SEDT is compared to another result produced by the same SEDT in a repeated experiment under unchanged conditions.

Visibility [C15]–[C16]

SEDTs are of value to operators of CPSs only if the encapsulated states and produced results are readily accessible. The following two characteristics dominate the visibility of SEDTs.

Introspection [C15]: This characteristic indicates the extent to which the state of an SEDT can be analyzed and is, therefore, primarily driven by its fidelity. A higher level of introspection allows user interaction and provides access to intermediate results.

Relevance to Security Use Cases. SEDTs can offer means to analyze the internal system state that is otherwise difficult to measure or simply

not accessible from the real-world system. New knowledge of the system and its behavior can be extracted by exploring the SEDT without fear of real-world consequences, with greater convenience and expedience and fewer physical or logical obstacles.

Indicator Considerations. The different manifestations of SEDTs (cf. Fig. 1) span a broad spectrum of interaction levels that can be ranked using qualifiers. For example, at the upper end of the spectrum, users can examine the state of the virtual machine by debugging the guest operating system and inspecting the running processes of control applications.

Data Capture [C16]: Data capture refers to the capability of the SEDT to monitor and record data during its execution. Depending on the use case, different types of data points can be of interest for each component of the SEDT (e.g., physical properties, application logs, network traces). We distinguish if the SEDT can capture the state of the entire system or only that of specific components. As with introspection, concerns may arise that relate to the fidelity and the resulting accuracy of the data produced.

Relevance to Security Use Cases. In general, the promise of the SEDT is to enable more comprehensive and easier data capture than what would be possible from the physical twin. For example, data capture is important to understand where manifestations of security risks occur (i.e., in which subsystem) and how they affect the physical process under control.

Indicator Considerations. Like introspection, the offered data capture features can be classified across all CPS layers in a qualitative manner. Examples include: Logging the state of virtual machines, collecting network traffic, acquiring debugging information of control applications, and recording simulation data.

Methodology and Time of Construction [C17]–[C21]

The methodology of construction can describe how the SEDT and its parts are built. In certain cases, the SEDT is built before the physical counterpart [C19]; in others, the SEDT is constructed after the physical counterpart (e.g., for already existing systems) [C18], or both can even be developed simultaneously [C17]. These characteristics are sometimes also grouped under the term "time of creation" [3]. In either of these scenarios, for a while only one instance could exist (the physical or the digital part), which could also affect other characteristics described in this section.

The chronology of the creation of the two parts also limits the methods and sources available to develop SEDTs. They can be built from specifications [C20], by learning [C21] (observing the behavior of the CPS), or a combination thereof.

Relevance to Security Use Cases. The methodology for building the SEDT can have ramifications when it is used for security. For example, building the SEDT entirely by learning from the CPS and then using it as a basis to generate data for creating a behavior-based IDS would lead to an unnecessary indirection. In this case, it seems more fruitful (e.g., in terms of accuracy) to directly use the original data.

Research and Engineering Challenges

Despite the great potential of SEDTs for security purposes, we are still in the infancy of this concept and face a series of notable challenges that need to be addressed to realize its benefits. CPS Emulation & Virtualization Tooling. One severe limitation is the emulation of field and control devices, such as programmable logic controllers (PLCs), since their hardware and software components are often proprietary and closedsource. However, the advent of PLCs with embedded Linux and the growth of open-source initiatives could alleviate this situation. Nevertheless, suitable system emulator targets will be required. Trade-Off Between Fidelity & Cost. Another challenge is to balance the fidelity of an SEDT and the effort of implementation such that target use cases are sufficiently supported while costs and development time are kept under control. Naturally, high-fidelity SEDTs necessitate the integration of sophisticated physical models and a (near-)complete coverage of components via emulations, which requires considerable implementation effort or is simply infeasible. On the other hand, imperfections of models are inevitable; thus, care has to be taken that wrong assumptions or mismatches will not lead to a false sense of assurance and, subsequently, wrong decisionmaking. One promising solution to keep the costs and time for approximating the physics manageable is to combine the conventional physicsbased approach with data-driven modeling if approximating through learning is sufficient for the intended purpose. It is also worth noting that there are additional factors, which may be interrelated with fidelity or cost, that need to be considered when implementing SEDTs. For instance, higher fidelity SEDTs may generate significant network traffic, thereby potentially affecting network performance or even the CPS itself (e.g., in the case of polling for synchronization).

Synchronization. Most of the described security use cases unlock their true value if SEDTs are synchronized with their corresponding CPSs. However, problems related to synchronization remain challenging for the community. For example, defining an initial state for synchronization and identifying which system inputs serve as stimuli and, hence, need to be replicated in the virtual environment requires further investigation. Other important aspects to consider are real-time constraints and timing issues, which could lead to the state of the SEDT drifting from reality. To handle such synchronization errors, mechanisms to recover from state mismatches are required.

Security Implications of SEDTs. While the promises of SEDTs may seem attractive, certain applications could also raise new concerns that potentially nullify the benefits. For instance, in the case of intrusion detection, the SEDT may be susceptible to the same vulnerability as its physical counterpart. Thus, attackers can potentially evade intrusion detection if malicious states are replicated, and the SEDT is equally affected by this vulnerability. It should also not go unnoticed that DTs, by themselves, may introduce additional cybersecurity risks [15]. Consequently, careful consideration should be given to securing the DTs and their connection to their physical counterparts.

Conclusion

Overall, we conclude that the DT paradigm holds promise for several CPS security applications. However, the limitations discussed above suggest that considerable research and engineering efforts will be required. Thus, SEDTs will not render traditional security concepts and approaches obsolete in the near future, if ever. Instead, we anticipate that they co-exist or that future SEDT technology will be used to further improve existing security solutions (e.g., testbeds, honeypots, IDSs). It is also worth highlighting that an SEDT is a software-only construct, meaning that its scope of application is naturally limited and, for instance, cannot serve as a substitute for HIL testing. On a final note, we urge the scientific community to clearly communicate the characteristics of SEDTs when presenting new solution proposals in order to prevent the nebulous view of the DT concept from being prolonged.

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REFERENCES

- E. Negri, L. Fumagalli, and M. Macchi, "A review of the roles of digital twin in CPS-based production systems," *Procedia Manuf.*, vol. 11, pp. 939 – 948, 2017.
- Y. Jiang, S. Yin, K. Li, H. Luo, and O. Kaynak, "Industrial applications of digital twins," *Philos. Trans. R. Soc. A*, vol. 379, no. 2207, 2021.

- H. van der Valk, H. Haße, F. Möller, M. Arbter, J.-L. Henning, and B. Otto, "A taxonomy of digital twins," in *Proc. AMCIS*, 2020, pp. 1–10.
- D. Jones, C. Snider, A. Nassehi, J. Yon, and B. Hicks, "Characterising the digital twin: A systematic literature review," *CIRP J. Manuf. Sci. Technol.*, vol. 29, pp. 36– 52, 2020.
- 5. M. Dietz and G. Pernul, "Unleashing the digital twin's potential for ICS security," *IEEE Secur. Priv.*, 2020.
- R. Mitchell and I.-R. Chen, "A survey of intrusion detection techniques for cyber-physical systems," *ACM Comput. Surv.*, vol. 46, no. 4, pp. 55:1–55:29, 2014.
- D. Holmes, M. Papathanasaki, L. Maglaras, M. A. Ferrag, S. Nepal, and H. Janicke, "Digital twins and cyber security – solution or challenge?" in *Proc. 2021 SEEDA-CECNSM*, 2021, pp. 1–8.
- M. Shafto, M. Conroy, R. Doyle, E. Glaessgen, C. Kemp, J. LeMoigne, and L. Wang, "Modeling, simulation, information technology & processing roadmap," *National Aeronautics and Space Administration*, 2012.
- A. C. Mora, S. Nadjm-Tehrani, E. Weippl, and M. Eckhart, "Digital Twins for Cyber-Physical Systems Security (Dagstuhl Seminar 22171)," *Dagstuhl Reports*, vol. 12, no. 4, pp. 54–71, 2022.
- A. Budiardjo and D. Migliori, "Digital twin system interoperability framework," Digital Twin Consortium, Tech. Rep., 2021.
- D. Liu, N. D. Macchiarella, and D. A. Vincenzi, "Simulation fidelity," in *Human Factors in Simulation and Training.* CRC Press, 2009, pp. 61–73.
- M. Roza, J. Voogd, and P. van Gool, "Fidelity considerations for civil aviation distributed simulations," in *Proc. AIAA Model. Simul. Technol. Conf. Exhib.*, 2000.
- M. Eckhart and A. Ekelhart, "A specification-based state replication approach for digital twins," in *Proc. Workshop Cyber-Physical Syst. Secur. Priv.*, 2018, pp. 36–47.
- C. Gehrmann and M. Gunnarsson, "A digital twin based industrial automation and control system security architecture," *IEEE Trans. Ind. Informat.*, 2020.
- C. Alcaraz and J. Lopez, "Digital twin: A comprehensive survey of security threats," *IEEE Commun. Surv. Tutor.*, 2022.

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