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Reliability Optimization of CPS by digital twining

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Abstract. Digital twining (DT) is a recent approach in designing, optimization, and exploitation of cyber physical systems (CPS). DT can be used to simulate the behaviour of the CPS during a failure event, allowing reliability engineers to identify areas of the system that are vulnerable to failure, the root cause of the failure and to develop strategies for prevention. In this paper the interest goes to designing CPS based on digital twining approach while maximizing CPS reliability. The most common CPS reliability requirements are investigated and their reliability optimization strategies when using DT are discussed.

1. Introduction

The industrial revolution (4.0 nowadays) asks for more digitalization in order to implement the Digital Factory [1, 7, 8, 10]. Digital twins (DTs) are powerful tools for reliability analysis, as they can simulate physical system (PS) behavior and performance over time. Using DTs to analyze reliability, engineers can gain valuable insights into factors contributing to system failure and identify improvement opportunities. Also, DTs can help improve CPS security by providing a virtual model which can be used to identify potential security threats and vulnerabilities, test security measures and protocols, and optimize security of systems and processes. In this paper some reliability requirements of cyber-physical systems (CPS) are addressed in order to identify reliability optimization procedures in DT implementation.

Moreover, DT can be used to perform Failure Mode and Effects Analysis (FMEA), in order to identify potential failure modes and their effects on system availability [2, 9, 13, 14]. Also, this involves analyzing the data collected from the DT to identify potential issues that could lead to equipment failures or downtime. The data collected can include information about the system's operating conditions, performance metrics, and environmental factors that may have contributed to the failure. In transportation (including maritime) the Automate Identification Systems (AIS) are valuable source of data when investigate accidents and other unavailability factors.

Machine learning algorithms or other data analytics tools can be used to identify patterns or anomalies in the data, including navigation maps and AIS data. DT may prove help in improving accuracy of failure mode identification, can validate FMEA assumptions, can evaluate the effectiveness of mitigation strategies and create conditions for continuous improvement of the CPS.

2. DT and CPS frameworks

According to IBM [15], "a digital twin is a virtual model designed to accurately reflect a physical object." As Möller mentioned [11] CPSs "use computations and communication deeply embedded in and interacting with physical processes by adding new capabilities to physical systems". For instance, a CPS in manufacturing may incorporate different types of technical items, from 3D scanners/printers to cloud assisted manufacturing. However, DT is different from CPS. According to Song et al [12], "CPS represent the integration of physical and embedded systems with communication and IT systems." Therefore, CPS is a type of engineered system that integrates physical components with computing and communication technologies to monitor and control physical processes. Examples of CPS include smart home systems, self-driving cars, industrial control systems, medical devices, autonomous ships. CPS can also be found in applications such as aerospace, defense, energy, and maritime infrastructure and services.

CPS requires a combination of hardware and software technologies, including sensors, actuators, microprocessors, communication protocols, and control algorithms. The integration of these components enables CPS to interact with the physical world, sense changes in the environment, and respond accordingly [3, 6, 11, 12].

It is clear that DT simulates environments using augmented and virtual models in order to study the behavior of systems, including CPS. In this way a DT is a digital clone of a CPS used to monitor and analyze the CPS behavior. While both DTs and CPS involve the integration of physical systems with digital technologies, they have different purposes and applications. DTs are primarily used for simulation and analysis, while CPS are used to control and optimize physical processes in real-time. Hence, DTs and CPS can be used together to improve the design, operation, and maintenance of physical systems. By creating a digital twin of a CPS, it is possible to simulate and test different scenarios, optimize performance, and detect potential problems before they occur.

A CPS framework starts with a PS that consists of sensors, actuators, and other components that interact with the physical environment. There are several frameworks that have been proposed for the design, implementation, and operation of CPS. In the following, some common components of a CPS framework are presented [3]:

- *Cyber System*: The cyber system (CS) includes hardware and software components that collect data from the PS, analyze it, and provide feedback to control the PS. In this way a CS is similar to DT, but CS is not a simulator like DT.
- *Communication Network*: A communication network is used to transmit data between PS and CS, as well as between different components of CPS.
- *Data Analytics*: Data analytics tools are used to analyze the data collected from the PS and provide insights that can be used to optimize performance, detect anomalies, and predict failures.
- *Control Algorithms*: Control algorithms are used to process the data collected from the CPS and determine the appropriate actions to be taken to control the CPS.
- *Security and Privacy*: DT frameworks must include measures to ensure the security and privacy of the data collected from the CPS, as well as the integrity and reliability of the control system.
- *Human-Machine Interface*: DT frameworks should include a human-machine interface that allows operators to interact with the system, monitor its performance, and make decisions based on the data collected from CPS.

These components are not exhaustive and may vary depending on the specific CPS application and context. However, they provide a general overview of the main elements of a CPS framework [4, 5].

When considering DT technology, this approach can be used to simulate processes, organizations, social communities etc. A DT framework for a CPS typically consists of several components that work together to create a virtual replica of a the CPS or processes from an organization. The most common components of a DT framework are:

- *Physical System*: The PS is the object or process that the DT is intended to replicate by digitalization. This can be anything from a machine or device to a complex system such as a factory or city, including maritime cyber-physical systems.
- *Data Sources*: Data sources are the inputs to the digital twin, and can include sensors, cameras, historical data, and other sources of information about the PS/CPS.
- *Data Analytics*: Data analytics tools are used to process the data collected from the PS and generate insights about its behavior and performance.
- *Modeling and Simulation*: The DT is created using models and simulation methods that represent the PS and its behavior. These models can range from simple mathematical models to complex simulations that incorporate multiple variables and interactions. Recently, the parallel processes simulations are possible through superdense time implementations.
- *Visualization and Interaction*: The DT makes use of 2D or 3D graphics, and may include interactive features that allow users to explore different scenarios and make decisions based on the data generated by the twin. For maritime transportation the maps of AIS generated data can be viewed.
- *Integration*: DT frameworks may need to embed other systems and technologies, such as cloud platforms, machine learning algorithms, or Internet of Things (IoT) devices.
- *Maintenance and Optimization*: DTs can be used to optimize the performance of the CPS, by predicting failures, identifying areas for improvement, and helping to test for new scenarios.

Therefore, the dependability requirements of any CPS depend on its intended use, its criticality to the operation of a larger system, and the consequences of failure. However, in general, CPS dependability requirements typically include the following:

- *Safety*: CPS must be designed and operated to ensure the safety of people, the environment, and the PS itself. This includes measures such as fail-safe designs, redundancy, and fault detection and correction.
- *Availability*: CPS must be available and operational when needed. This requires measures such as preventive maintenance, rapid response to failures, and backup systems to ensure continuity of operations.
- *Performance*: CPS must meet performance requirements, including accuracy, speed, and efficiency. This requires measures such as monitoring and analysis of performance data, optimization of control algorithms, and real-time decision-making.
- *Scalability*: CPS must be designed to accommodate growth and changes in the physical system or the operational environment. This requires measures such as modularity, interoperability, and flexibility in the design and operation of the CPS.

- *Reliability*: CPS reliability refers to the ability of the system to perform its intended functions accurately and consistently, without failures or errors. The following aspects have strong impact on CPS reliability: (1) CPS has to include redundancy in critical components to minimize the risk of failure and increase reliability; (2) CPS must undergo rigorous testing and validation to ensure that it meets reliability requirements, including tests for functional and non-functional requirements, such as performance, safety, and security; (3) CPS must be maintained and upgraded regularly to ensure that it continues to meet reliability requirements and remains up-to-date with changes in the operational environment; (4) CPS must be designed and operated with strong cybersecurity measures to prevent cyber-attacks and minimize the risk of cyber-related failures; (5) Human factors can impact the reliability of CPS, such as training and education of operators and maintenance personnel, and ensuring that they have the knowledge and skills necessary to operate and maintain the system effectively.

3. CPS reliability optimization by digital twining

Reliability optimization is a crucial aspect of CPS design as it ensures that the system can perform its intended function safely and efficiently. When creating a DT, some reliability optimization methods of the PS should be taken into consideration [16]. One commonly used method is probabilistic risk assessment (PRA), which is a mathematical technique for estimating the probability and consequences of system failures. PRA involves several steps, including:

- *Identifying failure modes*: This involves identifying the ways in which the system can fail, such as component failures, software errors, or human errors.
- *Estimating failure probabilities*: This involves estimating the likelihood of each failure mode occurring, based on historical data, expert judgment, or other sources of information.
- *Analyzing consequences*: This involves analyzing the consequences of each failure mode, including the impact on system performance, safety, and other factors.
- *Developing mitigation strategies*: Based on the results of the analysis, mitigation strategies can be developed to reduce the probability and consequences of system failures. These may include redundancy, maintenance procedures, operator training, or other measures.

Other methods that can be used to optimize system reliability of CPS include fault tree analysis (FTA), reliability block diagrams (RBD), Markov analysis (MA), Bayesian networks (BN), and machine learning (ML) approaches. These methods can help identify potential failure modes, estimate probabilities of failure, and evaluate the impact of various mitigation strategies.

FTA requires careful consideration of the system design and operational environment, as well as an understanding of the failure modes and probabilities of each contributing factor. The FTA process involves several steps, including:

- *Identifying the top event*: This is the failure mode of interest that the analysis is focused on.
- *Identifying the contributing factors*: This involves identifying all the potential factors that could contribute to the top event. These factors may include hardware failures, software errors, operator errors, environmental factors, and other variables.
- *Constructing the fault tree*: The fault tree is constructed by organizing the contributing factors in a logical and hierarchical manner, with the top event at the top of the tree and the contributing factors as branches.

- *Evaluating the probabilities*: The probabilities of each contributing factor are evaluated, based on historical data or expert judgment.
- *Analyzing the results*: The results of the FTA are analyzed to identify the most critical factors that contribute to the top event, and to develop strategies for mitigating these contributors.

RBDs are used to represent the CPS as a series of blocks, with each block representing a component or subsystem of the system. The RBD method involves several steps, including:

- *Identifying the components*: This involves identifying all the components or subsystems of the CPS that need to be included in the analysis.
- *Organizing the components*: The components of CPS are organized in a logical and hierarchical manner, with the most critical components at the top of the diagram and the less critical components below.
- *Defining the reliability of the components*: The reliability of each component is defined using probability or failure data, which can be obtained from historical data or expert judgment.
- *Combining the reliability of the components*: The reliability of the system is then evaluated by combining the reliability of the individual components in a logical manner. This may involve using "and" gates, which require all components to function for the system to operate, or "or" gates, which allow for redundancy or alternative components to be used.
- *Analyzing the results*: The results of the RBD are then analyzed to identify the most critical components and to develop strategies for improving system reliability.

MA is a powerful tool for evaluating the reliability of CPS over time, as it allows for a detailed analysis of the system behavior and the impact of various factors on system reliability. The steps of this methods are:

- *Defining the states of the system*: This involves identifying all the possible states that the CPS can be in, such as operating normally, operating in a degraded state, or in a failed state.
- *Constructing the Markov chain*: The Markov chain is constructed by defining the transition probabilities between each state, based on the probability of a component failing, the probability of a repair being successful, and other factors.
- *Evaluating the steady-state probabilities*: The steady-state probabilities of the system being in each state are evaluated using matrix algebra or other methods.
- *Analyzing the results*: The results of the MA are analyzed to identify the most critical states and to develop strategies for improving system reliability, such as increasing redundancy, improving maintenance procedures, or improving system monitoring.

One way to use BNs in CPS reliability optimization is to use Markov chain Monte Carlo (MCMC) sampling to estimate the probabilities of system failure under different scenarios. Another way to use BNs is to perform sensitivity analysis to determine the impact of changes in component reliability on the overall system. This can help designers identify which components are most critical to the system's reliability and prioritize their optimization efforts accordingly.

There are some ways in using ML algorithms in reliability optimization:

- *Support Vector Machines (SVMs)*: SVMs are a type of supervised learning algorithm that can be used for classification and regression analysis. In CPS, SVMs can be used to predict the reliability of a particular component based on past performance data.

- *Random Forests (RF):* RFs are a type of ensemble learning algorithm that can be used also for classification and regression analysis. In CPS engineering, Random Forests can be used to identify the most important factors that affect the reliability of the system and to predict the reliability of the system based on these factors.
- *Deep Learning (DL):* DL is a subset of ML that uses deep neural networks to analyze and learn from data. In CPS engineering, DL can be used to predict the reliability of the system based on historical performance data, sensor data, and other inputs.
- *Reinforcement Learning (RL)*: RL is a type of machine learning that uses trial and error to learn from experience. In CPS engineering, RL can be used to optimize the control policies of the system to maximize reliability.
- *Bayesian Optimization (BO)*: In CPS, BO can be used to optimize the parameters of the system to maximize reliability.

The use of digital twin technology and implementing the above mentioned strategies can help manage reliability optimization of CPS by providing real-time monitoring, predictive maintenance, optimization of control strategies, and design improvement. This technology can help reduce downtime, maintenance costs, and improve the overall reliability of the CPS.

DT technology can be used to manage reliability optimization of CPS in the following manner [16]:

- *Creating a virtual model*: DT technology involves creating a virtual model of the CPS that mirrors the physical system. This model can be used to simulate the behavior of the system and predict potential failure points. The virtual model can also be used to test optimization strategies before implementing them in the physical system.
- *Real-time monitoring*: DT technology can be used to monitor the performance of the CPS in real-time. By collecting data from sensors and other sources, the DT can identify potential failure points and notify the operator before the system fails. This can help prevent downtime and reduce maintenance costs.
- *Predictive maintenance*: DT technology can be used to predict when maintenance is needed for the physical system. By analyzing data from the sensors and other sources, the DT can identify when components are likely to fail and schedule maintenance before the failure occurs.
- *Optimization of control strategies*: DT technology can be used to optimize the control strategies of the CPS. By simulating different control strategies in the virtual model, the DT can identify the most effective strategy for optimizing reliability.
- *Simulation of failure scenarios:* DT can be used to simulate failure scenarios in the virtual model of the CPS. This can help identify potential failure points and test the effectiveness of optimization strategies before implementing them in the CPS.
- *Design improvement*: DT technology can be used to identify design improvements that can enhance the reliability of the CPS. By simulating different design options in the virtual model, the DT can identify the optimal design that maximizes reliability.

4. Conclusions

DT technology can be used to optimize the CPS reliability when implemented for various fields towards modern smart cities, smart environments and digital factories. The paper has described the CPS reliability requirements, the CPS optimization reliability common approaches and how a digital twin implementation may benefit in monitoring and optimizing a CPS.

Future investigations will be directed to the influence of every DT component in increasing/optimizing the CPS reliability and to theoretical developments on DT as digital dynamic systems.

References

[1] Bordeleau Francis, Combemale Benoit, Eramo Romina, van den Brand Mark, Wimmer Manuel. *Towards Model-Driven Digital Twin Engineering: Current Opportunities and Future Challenges*. ICSMM 2020 - International Conference on Systems Modelling and Management, Jun 2020, Bergen, Norway. hal-02946949

[2] Futalef Juan-Pablo; Di Maio Francesco; Zio Enrico: *Grey-Box Models for Cyber-Physical Systems Reliability, Safety and Resilience Assessment*, Proceedings of the 32nd European Safety and Reliability Conference (ESREL 2022), Edited by Maria Chiara Leva, Edoardo Patelli, Luca Podofillini, and Simon Wilson, Research Publishing, Singapore. doi: 10.3850/978-981-18-5183-4_S20-05-564-cd

[3] Gougeon P.: Hamelin E.: *Development complexity of Cyber-Physical Systems: theoretical and practical benefits from Pre-Integrated Architectures*. J Smart Environ Green Comput 2023;3:3-17. https://dx.doi.org/10.20517/jsegc.2022.17

[4] Griffor E.; Greer C.; Wollman D.; Burns M.: *Framework for Cyber-Physical Systems: Volume 1, Overview, Special Publication* (NIST SP), National Institute of Standards and Technology, Gaithersburg, MD, 2017, [online], https://doi.org/10.6028/NIST.SP.1500-201 (Accessed April 16, 2023)

[5] Griffor E.; Greer C.; Wollman D.; Burns M.: *Framework for Cyber-Physical Systems: Volume 2, Working Group Reports, Special Publication* (NIST SP), National Institute of Standards and Technology, Gaithersburg, MD, 2017 [online], https://doi.org/10.6028/NIST.SP.1500-202 (Accessed April 16, 2023)

[6] Hensel, M. (Ed.), & Bier, H. H. (2022). *Cyber-Physical Architecture #5 Interdisciplinary Data-integrated Approaches*. Spool. Journal of Architecture and the Built Environment, 9(1 #5).

[7] Lee D.; Kim C.-K.; Yang J.; Cho K.-Y.; Choi J.; Noh S.-D.; Nam S.: *Digital Twin-Based Analysis and Optimization for Design and Planning of Production Lines*. Machines 2022, 10, 1147. https:// doi.org/10.3390/machines10121147

[8] Lee Jay; Bagheri Behrad; Kao Hung-An: *A Cyber-Physical Systems architecture for Industry 4.0-based manufacturing systems*, Manufacturing Letters 3 (2015) 18–23, http://dx.doi.org/10.1016/j.mfglet.2014.12.001

[9] Miqueles Leonardo; Ahmed Ibrahim; Di Maio Francesco; Zio Enrico: *A Grey-Box Digital Twin-based Approach for Risk Monitoring of Nuclear Power Plants*, Proceedings of the 32nd European Safety and Reliability Conference (ESREL 2022), Edited by Maria Chiara Leva, Edoardo Patelli, Luca Podofillini, and Simon Wilson, Research Publishing, Singapore. DOI: 10.3850/978-981-18-5183-4_S24-05-579-cd

[10] Monsone C.; Mercier-Laurent, E.; János, J.: *The Overview of Digital Twins in Industry 4.0:*

Managing the Whole Ecosystem. In Proceedings of the 11th International Joint Conference on Knowledge Discovery, Knowledge Engineering and Knowledge Management (IC3K 2019), pages 271-276. DOI: 10.5220/0008348202710276

[11] Möller Dietmar P.F.: *Guide to Computing Fundamentals in Cyber - Physical Systems Concepts, Design Methods, and Applications*, Springer, 2016.

[12] Song Houbing; Rawat Danda B.; Jeschke Sabina; Brecher Christian: *Cyber-Physical Systems Foundations, Principles and Applications*, Elsevier, 2017.

[13] Specht Cezary; Rudnicki Jacek: *A Method for the Assessing of Reliability Characteristics Relevant to an Assumed Position-Fixing Accuracy in Navigational Positioning Systems*, Polish Maritime Research 3 (91) 2016 Vol. 23; pp. 20-27 DOI:10.1515/pomr-2016-0028

[14] Zhou Buxiang; Cai Yating; Zang Tianlei; Wu Jiale; Sun Binjie; Chen Shi: *Reliability Assessment of Cyber–Physical Distribution Systems Considering Cyber Disturbances*. Appl. Sci. 2023, 13, 3452. https://doi.org/10.3390/app13063452

[15] ***, https://www.ibm.com/topics/what-is-a-digital-twin

[16] ***, https://www.controleng.com/articles/how-digital-twins-can-enable-optimization/.