Faulty Behaviors in Cyber-Physical Production Systems for Analysis Optimization and Maintenance

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***Abstract*—The challenges of the fourth industrial revolution (Industry 4.0) seem to bridge the gap between the traditional design automation context and the manufacturing world. In order to support the safety of an entire production plant, a structured methodology for the modeling of Cyber-Physical Production Systems (CPPSs) is required. Constructing a simulable model of a production line is crucial to ensure adequate maintenance in a CPPS. However, this is complicated due to the presence of highly heterogeneous components: ensuring an accurate and correct simulation of the production line is a critical issue. In this perspective, Verilog-AMS is a promising solution, as it allows to cover different levels of details, from transistor-level and digital components to multi-physical dynamics.**

This thesis proposes a new way of modeling faults in different physical domains using the Verilog-AMS language and generating faulty data to support the predictive maintenance process. In particular, the mechanical parts of the systems have been analyzed through the physical analogies with the electrical domain. Moreover, a mechanical fault taxonomy has been derived by injecting electrical fault models. Other tools that allow modeling a CPS (*e.g.*, Matlab/Simscape, and OpenModelica) have been analyzed to compare them with our approach, pros and cons are shown in this report. The faulty synthetic data has been combined/fused with real data from the production line in order to identify early possible disruptive failures. Finally, an initial way to use synthetic data to create a digital shadow and twin has been created and published.

***Index Terms*—Digital Twin, Industry 4.0, Fault Modeling, Functional Safety**

I. Introduction

In the Industry 4.0 scenario, simulating production lines is of utmost importance to support maintenance tasks, predict and estimate the evolution of all aspects of the line. However, the complexity of such systems and the presence of multi-physics components make the construction of accurate models challenging. Constructing such a holistic representation of the production line, called the "digital twin", is an interesting and open research problem. One of the most attractive applications of the digital twin is to support maintenance strategies, by generating useful information to predict when faults may arise, and anticipate corrective actions. Applying fault analysis to the production line requires indeed the availability of data series of the machinery operating conditions both in normal conditions and in presence of faults [1], [2]. However, faults are rare at the beginning of lifetime of the plant, and forcing the generation of faulty behaviors by breaking the production line machines it is not feasible. In this scenario, the digital twin instrumented with fault models could generate data series related to the nominal behavior of a machinery and also in presence of different types of faults.

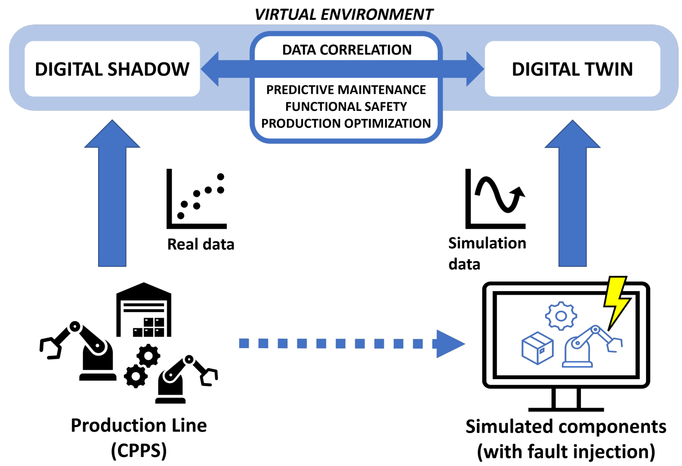

Fig. 1. Conceptual overview of the proposed methodology. The digital shadow and twin creates the virtual abstraction of a production line enabling further analysis.

In this perspective, it is fundamental to identify a framework that allows to build the different parts that compose the digital twin. For example, graphical tools like Modelica and Simulink use a block-based notation and model each piece of machinery as a black box, which hides the internal dynamics of the component. Due to this internal configuration of these simulators, it is difficult to systematically alter the internal dynamics of each component. An alternative approach is to use frameworks based on languages, like Verilog-AMS: such languages require explicitly modeling system evolution as differential and algebraic equations. These formats impose a higher effort during the construction of the model; however, this modeling style expresses all system behaviors and it allows to inject faults and faulty behaviors at any level of detail in a systematically way.

Another significant difference between using tools or languages arises when the cyber portion of the production line needs to be modeled. Graphical tools like Modelica and Simulink cannot reproduce HW and SW accurately, since they focus on multi-physical descriptions, and the cyber dimension is beyond their interest. Vice versa, the choice of a language like Verilog-AMS, based on the HDL Verilog, allows to naturally support the cyber portion of the system in the same simulation infrastructure.

This thesis aims to show how Verilog-AMS can be effectively used to model production line components and to inject faults in their descriptions. Other key points of this work are the analysis of transistor-level faults and the correlation of the synthetic data with the real data, enabling a digital twin for the maintenance process. The proposed flow is represented in Figure 1, in details:

- an accurate model of the line component is implemented in Verilog-AMS, by modeling the component dynamics as differential and algebraic equations. These models have also been described as electrical circuit exploiting the physical analogies;
- faults are injected in the Verilog-AMS model, to reproduce faulty behaviors that alter the regular operation of the component;
- the injected model is used to simulate the faulty component version and to generate data traces for predictive maintenance or further correlation analysis with the real data;
- transistor-level faults and behaviors have been analyzed.

The report is structured as follows: Section II depicts an overview of the results already achieved. Then, Section III proposes future extensions and research directions for our Ph.D. thesis.

II. Achieved Results

The methodology steps already published are highlighted into the Figure 1. Finding out the efficient methods and protocols to retrieve data from the shop floor is essential to obtain a digital shadow of a production line. In [3] an overview has been made on the similarities that can be found between the Electronic Design Automation (EDA) world and modern production lines, with a focus on industrial sensors. In order to perform in-depth analysis on a production line, however, it is not sufficient to retrieve data from the line and analyze it, but we need to compare it with synthetic data, *i.e.* execution traces generated through simulation.

Therefore, in [4] we analyzed the best way to generate multi-physics models that could describe components of our production line. The language we chose is Verilog-AMS, as it is very flexible and it can support both cyber and analog parts. Furthermore, we analyzed the failure models and tested them by simulating the failed systems to generate faulty simulation traces. Work [5] is also an extension of the previous one, in which we also compare other techniques for modeling multi-physics systems, among them, Modelica and Simulink/Simscape. Next, in [6] by analyzing data generated from a faulty model described in Simulink, we were able to identify critical standards and thresholds that would allow us to identify anomalies in the physical model; this is the first step towards predictive maintenance.

In parallel, through works [7] and [8], we have analyzed different techniques to model a digital shadow and a digital twin, focusing on the study of data and extra-functional properties. Then, continuing the main research group research, in papers [9] and [10] we analyzed different analog faults modeled at transistor level (from the emerging standard IEEE P2427). Starting from these models described at a low level, we are working to abstract them and transport them into Verilog-AMS behavioral descriptions.

In this context, we looked for a way to exploit the physical similarities between the mechanical and electrical domains. Our goal is to create circuits that are equivalent to mechanical systems at the behavioral, *i.e.*, equation level. By simulating these electrical circuits, we constructed a new taxonomy of mechanical faults. Specifically, we derived this taxonomy by injecting classical electrical faults into the equivalent circuit and studied their behavior. This work is presented in the papers [11] and extended with more results in [12]. Now, the focus of our work moves to building an algorithm to determine where to inject faults into the multi-domain models that compose the digital twin.

III. Thesis Completion

In the near future, we plan to improve and extend the proposed methodology by considering additional aspects of the production line and more sophisticated models. In particular, the methodology will be validated on a real production machine that is present in the *ICE Laboratory* located in Verona, Italy. The laboratory is equipped with the state of the practice Industry 4.0 compliant machineries. As future works we plan to verify the analogies on more complex designs and extend the fault taxonomy.

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