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Digital Twin Technology: Modeling a Circuit Board for Simulating Electronic Device Operation

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Abstract. We report on possible applications of the digital twin technology. We analyzed digital twin structures of various types considering their parameters in terms of usage. A circuit board model was designed and the device behavior was predicted during its operation at high temperatures close to critical or above critical values. The data obtained allows to optimize the device operation regimes and produce timely adjustments to the design.

1. INTRODUCTION

Currently, the digital twin (DT) technology is of paramount interest, as it promises product condition data utilization to identify the failures causes, optimize supply chains, improve product quality, and increase production efficiency. Despite its novelty, the technology has drawn the attention in various fields of Industry 4.0. Literature on the principle of operation and DT technology provides a wide range of its different definitions [1–3]. The DT technology has gone through several development stages — from physical connections with industrial products to virtual processes associated with natural objects. With scientific and technological progress, DT acquires more and more interpretations with experts rephrasing its definition to fit their application area. Thus, DT is difficult to consider without taking into account the context and field of its use, and as a result, there is no precise or accurate definition of DT and its list of constituent parts.

In its general form DT is designed to solve increasing complexity problems of current systems. A solution can be digital technologies combining the numerical core for more efficient modeling, designing, building, and maintaining of such complex systems. Digital tools should comprehensively describe an object and work in close information connection with it, integrate seamlessly with each other to ensure digital continuity of the product manufacturing environment and track all the stages of the product life cycle (PLC). Individual PLC stages require developing a digital documentation, from the design stage to the operation ones. Applying the DT technology, the design stage means "digital model – product prototype", not "finished product – its digital model". This approach enables the design engineer to simulate and analyze the product operation under various scenarios at every stage of product development.

For example, the proper device functioning is provided by correct thermal regime selection, optimal approach to artificial cooling, material selection for cases and radiators of the designed system [4–5]. The DT technology can be useful to analyze temperature gradients and heat flows occurring during the operation of a printed circuit board, as they can significantly affect the performance of individual system components. Such an analysis allows to gain some insight into the

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product performance as well as produce timely adjustments to its design with minimal losses.

2. DIGITAL TWIN COMPOSITION

At its core, the DT technology itself is not the latest unique technology. It is a combination of many digital technologies that help achieve business results and benefit various industries. Based on the foregoing, we propose the following definition of DT:

The Digital Twin is a set of approaches designed to solve a problem resulting from the growth in today's systems complexity, as well as multi-component and multi-functional products, outpacing the growth in the capabilities of tools for their design, manufacture, and safe maintenance. The DT basic structure contains three components:

– The physical part which is the basis for a virtual model and the main source of data development;

– The virtual part is responsible for modeling, decision making and management of the physical part. The object digital model is based on modeling both the object itself and its behavior, followed by verification, validation and certification of these models;

– The connection part unites all the incoming components and ensures the system operation in a coordinated manner.

Based on the three-component model, the idea of including two more components was proposed: *services* (functioning services) and *data* (central storage of information), as shown in Fig. 1.

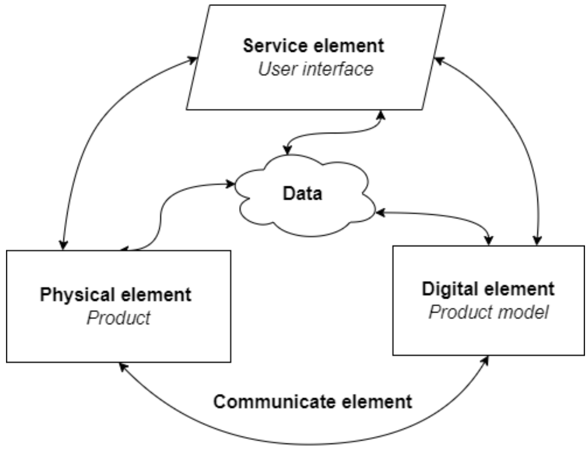

Fig. 1. Five-component digital twin model.

Services increase the interaction convenience with external systems and ensure the designed system reliability and performance.

The data allows tracking the entire system performance and preparing the foundation for future developments. The data measured during the operation is used to aggregate new information on its basis. By combining data from various sources, DT can predict the physical object technical condition. DT can also be used to predict the system response to critical security events.

Existing research on the DT practical application provides the main technologies and methods used in each block of the DT five-component model; Table 1 demonstrates the composition of each component.

Table 1. The digital twin composition.

Virtual DT element	Physical DT element	Central information storage
3D solid modeling; Physical processes modeling; Modeling the behavior of an object; Rule based models; Model consistency analysis; Model integration; Verification, validation and certification of models.	Sensors; Soft sensors; WSN (wireless sensor networks); Video surveillance systems; Embedded systems; Systems for optimizing the location of sensors.	Data storage; Data modeling; Data cleaning; Data conversion; Data integration and fusion; Data analysis and visualization; Data mining; Data integrity check; Ensuring data security.
Service element	**Communications between the DT elements**	
Resource and service management; Services description; Service encapsulation; Providing a human-machine interface; Data visualization; Search systems and results comparison; Monitoring of equipment operation; Resource consumption optimization.	Analysis of the compatibility of communication protocols for the internal elements of the DC and communication with external systems; Coordination of operating modes of interfaces; Additional communication devices in the various types case of "last mile"; Providing wireless communication; Application programming interface design (implements communication between different software modules using an application layer protocol); Standards development and specifications harmonization for communication protocols between the DT components and external systems.	

Table 2. Digital twin maturity levels.

Level	Structure	Communication with the physical elements	Use of artificial intelligence
1. Pre-digital twin	Virtual model with a focus on pre-testing	Impossible	not provided
2. Classic digital twin	Virtual model of a physical object, physical element	Monitors performance, technical condition, timely maintenance, provides updates in batch mode	not provided
3. Adaptive digital twin	Same as level 2, but with responsive user interface	Performance check, technical condition, timely maintenance, real-time updates	Possible training with a teacher.
4. Intelligent digital twin	Same as level 3, but with reinforcement learning	Obtaining information about the state of the environment in real time	Training is provided both with and without a teacher.

As can be seen from the DT composition, physical elements serve as the basis for a virtual model development. These include various surveillance systems, physical subsystems, sensors and systems for their optimal positioning. A virtual element can contain various technologies for modeling the object itself and its behavior with possible subsequent analysis, verification and model validation. Connections must be compatible in order to communicate with both internal DT nodes and external systems, as well as provide wireless communication. Data is a storage that must comply with information security requirements and provide various data manipulations. Services allow encapsulating processes and provide a convenient human-machine interface, analysis and optimization of resource consumption [6].

The DT concept implies its functioning at all PLC stages. With the product development, its DT also develops requiring the introduction of new functionality. Therefore, the DT composition can change significantly during PLC. To assess the DT development, four maturity levels are distinguished [7]; they are shown in detail in Table 2.

Level 1. Pre-digital twin. This level includes the object digital versions. They store its main characteristics and allow modeling in the digital dimension.

Level 2. Classic DT. The DTs of this level have collective characteristics of a batch, series or other subset of objects. They help predict manufacturing costs, take into account possible risks, collect and structure mass information about objects.

Level 3. Adaptive DT. The DT of this level is capable of real-time information exchange with a physical object while implementing the 2nd level DT functions.

Level 4. Intelligent DT. The DT of this level possesses all the capabilities of a Level 3 DT with the artificial intelligence strengths, which allows to make predictions based on ready-made templates without making mathematical calculations.

3. MODELING A CIRCUIT BOARD FOR SIMULATING ELECTRONIC DEVICE OPERATION

In this paper, the first maturity level DT model has been considered on example of the circuit board developed according to the electrical circuit diagram shown in Fig. 2. This circuit provides power to the board, receiving 75V at the input, lowering them and distributing them among various blocks of the device. In addition, the circuit under study allows, upon receipt of a control signal, to complete the operation of the device after a certain predetermined time interval. Such schemes are used, for example, in the field of alarms. Since this circuit receives a rather high voltage at the input and a lot of power is released on the components, one of the main factors affecting its performance is the heating of the components. The failure of one of the components can lead to the inoperability of the entire circuit, which can lead to a breakdown of the entire device or its incorrect operation. Therefore, it was decided to conduct a simulation to study the behavior of the board under various operating modes. The product developed according to the technical specifications available, must operate at a maximum ambient temperature of 50 °C with every element having its maximum temperature 100 °C in the same conditions.

Since the device, as well as the board, are currently at the development stage, it is not possible to conduct real tests, however, the heating indicators of the board components are critical for the operation of the entire device, and understanding the degree of thermal load is important already at the design stage. It was decided to use digital twin technology to simulate the operation

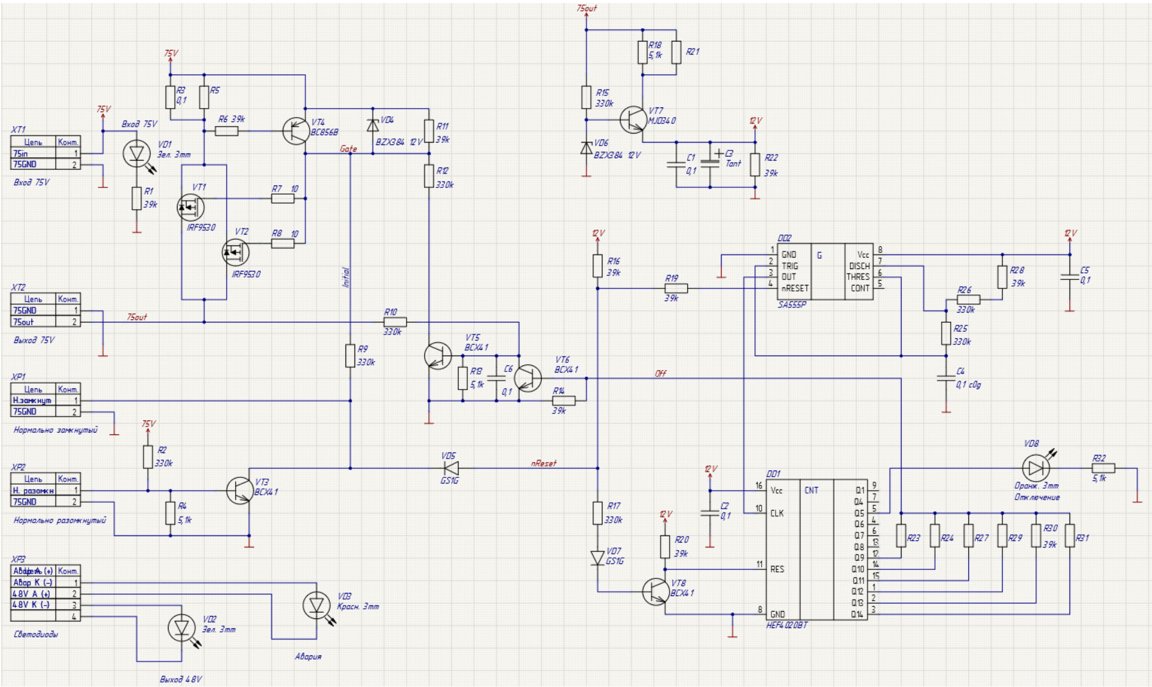

Fig. 2. Electrical circuit diagram of the simulated board.

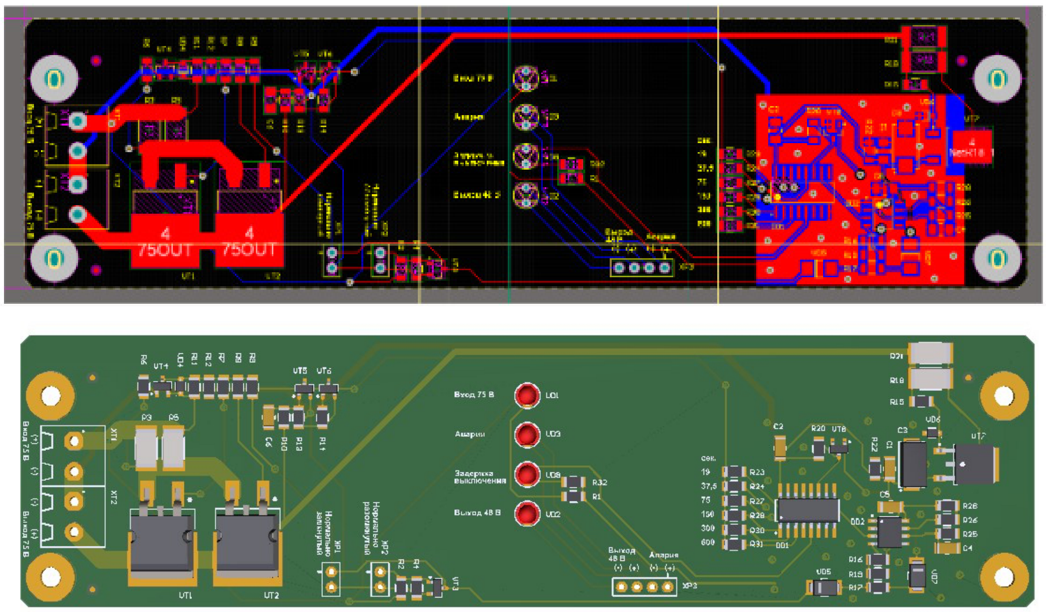

Fig. 3. Board simulation result in Altium Designer.

of the board and determine the need for additional cooling or replacement of components.

We chose the COMSOL Multiphysics software platform to model the thermal process, as it allows to make various calculations, solve a wide range of problems (also combining ongoing physical processes), use the finite element method, finite volume method and finite difference method. In addition, this platform allows to set the user's mathematical models and has its own environment for developing personalized user calculation applications [8].

The first modeling stage is shown in Fig. 3. It involves the circuit board model development in Altium Designer, since it links images of graphic elements to their footprints and sets their parameters.

When exporting a model from Altium Designer to COMSOL Multiphysics directly, some data is lost because of the lack of a strong graphical CAD editor core inside both software packages. The model import also results in the large amount of data loss, therefore, numerous errors occur. Correcting the errors directly inside the COMSOL Multiphysics software can be time-

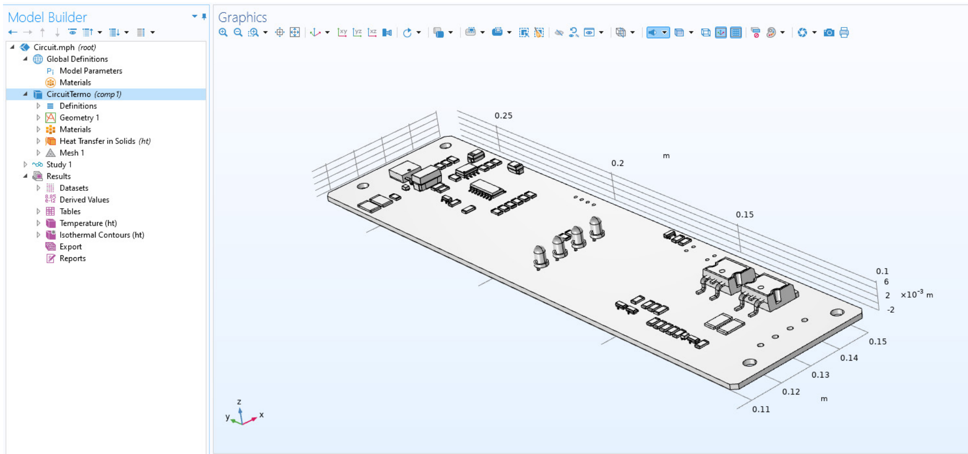

Fig. 4. The result of importing a model into COMSOL Multiphysics from SolidWorks.

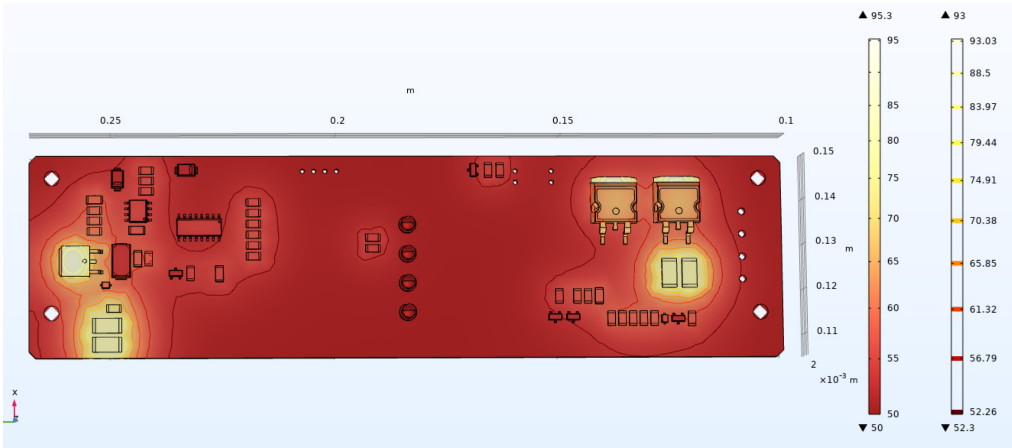

Fig. 5. Thermal gradient simulation result in Comsol Multiphysics.

consuming. The optimal solution could be to sequentially export and refine the model in three different design systems:

– Altium Designer;
– SolidWorks;
– COMSOL Multiphysics.

Exporting a model from Altium Designer to SolidWorks allows ignoring pads and conductive tracks, as they are not taken into account in the estimated calculation. In SolidWorks various conjugation errors are fixed and some elements, for example fillets, are removed. These elements do not affect the calculation, but complicate the modeling process. After processing in SolidWorks, the model is imported into COMSOL Multiphysics without errors, as seen in Fig. 4.

The first step in importing the model into COMSOL Multiphysics is an "empty" model that contains information only about the component’s dimensions on the board and their location, however, it does not contain physical characteristics. The next step is to define the materials and set their characteristics to the components on the board. The materials were taken from the datasheets for the components used. If the required materials characteristics cannot be found in the built-in libraries of the software package, they should be entered independently. The most important characteristics to solve thermal problems are the following:

– specific heat at constant strain;
– density;
– thermal conductivity;
– coefficient of linear expansion;
– thermal diffusivity.

Based on the electrical circuit, the power values for the electronic components were set and simulation was carried out.

The simulation result is the temperature board gradient, shown in Fig. 5. It allows evaluating the heating degree of each component or point on the board at various ambient temperatures [9]. Basically, the heating of the components occurs due to the fact that the components dissipate more power, participating in the provision of power to the device. In order to solve the problem of heating, you can use additional cooling elements, such as radiators, however, this will lead to an

Table 3. The simulation result of heating under different thermal conditions.

Component	*T*, (°C) at 40 °C	*T*, (°C) at 50 °C	*T*, (°C) at 60 °C
VT1, VT2 IRF9530	85	95	105
VT7 MJD340	74	88	98
R18	64	78	87
R3	65	77	86

increase in the dimensions of the board, which will entail changes in the entire design of the device in which this board is involved. It is also possible to replace components that will potentially experience overheating with more reliable ones, however this will increase the cost of the entire device.

Modeling within the framework of this stage of the project showed that all components of the board experience load within acceptable ranges specified in the technical documentation, which makes it possible to avoid the use of heat sinks and an increase in the size of the board or a change in the component base.

To evaluate the board behavior in critical temperature conditions, simulation was carried out at various ambient temperatures, and the temperatures of the "hottest" board elements were obtained; they are presented in Table 3.

These elements at critical temperatures have the highest heating values, the difference between the temperature on the board surface and the temperature of the hottest element surfaces is about 50 °C, which is normal and satisfies the requirements of the specification for the board. At the next work stages, based on the board tests fact, we plan to analyze the necessity to improve the mathematical apparatus of COMSOL Multiphysics, as well as the possibility of introducing artificial intelligence to analyze the data obtained.

4. CONCLUSION

Within this study framework, we have analyzed the DT technology application areas and described the general characteristics of the DT composition. We also analyzed the total DT composition based on DT utilizing data. Thus, the constructing basics of a virtual object image were investigated and five main DT structure parts were identified. The printed circuit board model was created for the import into COMSOL Multiphysics. The designed simulation circuit board model allowed to investigate the temperature characteristics of the board under various operating modes. The data obtained contributed to the understanding of the board behavior at high temperatures. Currently, we work on the assembly of the board designed to test, compare and analyze in terms of the simulation results.

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