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Role and Importance of Digital Technologies in the Development of Smart Products

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Abstract ***- The central place inside the fourth industrial revolution (Industry 4.0) belongs to the development of smart products and services. Smart technical products are also called "cyber-physical systems" (CPS) and they represent a combination of material and nonmaterial components, so that in addition to performing a work function, they also have the possibility of networking and mutual communication. For the development of smart products, there are new VDI 2206 recommendations dated from 2021. They present a model of interdisciplinary system architecture and an engineering approach for the development of smart products. This model does not include methods and tools that should be used in the implementation of engineering projects. The paper demonstrates the role and importance of digital technologies in the development of smart products, as well as their application in separate stages of product development.***

Key words: ***Industry 4.0, smart product development, design model, digital technologies***

I. INTRODUCTION

Industry 4.0 (I4.0) implies complete digitization of all production processes and the application of digital technologies when creating an idea for a product, organization and realization of production, process control and provision of industrial services. The implementation of I4.0 is based on the perfect integration of components related to the technology (information) and humans. The spectrum of technologies that support I4.0 is quite wide. These include Artificial Intelligence (AI), The Internet of Things (IoT), Virtualization Technologies (Digital Twins), Cloud Computing, Horizontal and Vertical System Integration, Big Data and Analytics, etc. [1, 2].

Contemporary engineering activities are characterized by high interdisciplinarity, networking, complexity and heterogeneity. A close interaction between the disciplines of mechanical, electrical and software engineering is necessary. A network of smart systems interconnected via the Internet of Things and Services flexibly adapts system behavior to changing boundary conditions, work situations and user requirements. There is also a requirement for independent detection and correction of possible poor decisions. In order to fulfill this, it is necessary to define interdisciplinary system architecture and an engineering approach based on a suitable model.

II. SMART PRODUCT DEVELOPMENT MODEL

A. Model Structure

Adequate reference models and accompanying technical infrastructure are extremely important for the development of innovative smart products. In this sense, the new improved V-model for the development of smart products plays an important role. The starting point of this approach is the V-model that describes mechatronic engineering (VDI 2206 from 2004), as well as the basics given in [3].

In the context of the V-model (VDI 2206) [4], the letter "V" stands for the deconstruction of the system into its constituent parts on the left arm and the gradual synthesis of those parts and subsystems into a whole technological system on the right arm. The qualities of the product under development are regularly examined and validated along these two "V"-shaped arms. As a result, the "proper" system (validation) is constructed in the "right" manner (verification).

Essentially, the suggested new V-model comprises of three strips (see Fig.1). The primary tasks and activities are described by the middle bar (orange). The claims handling procedure is shown in the inner (yellow) bar. Modeling and analysis-related operations are represented by the outer (blue) bar. Lines with disciplines are graphically shown in all three bars at the bottom of the V-model. Such a graphic illustration aims to emphasize how the definition of system elements depends on intricate details both inside and across the various disciplines. Thereby, the interaction and cooperation across the aforementioned disciplines is the key to success. Mechanical engineering, electronics / electrical engineering, software engineering, as well as pneumatics, hydraulics, optics, humanities, etc., are just a few of the possible disciplines that could be engaged.

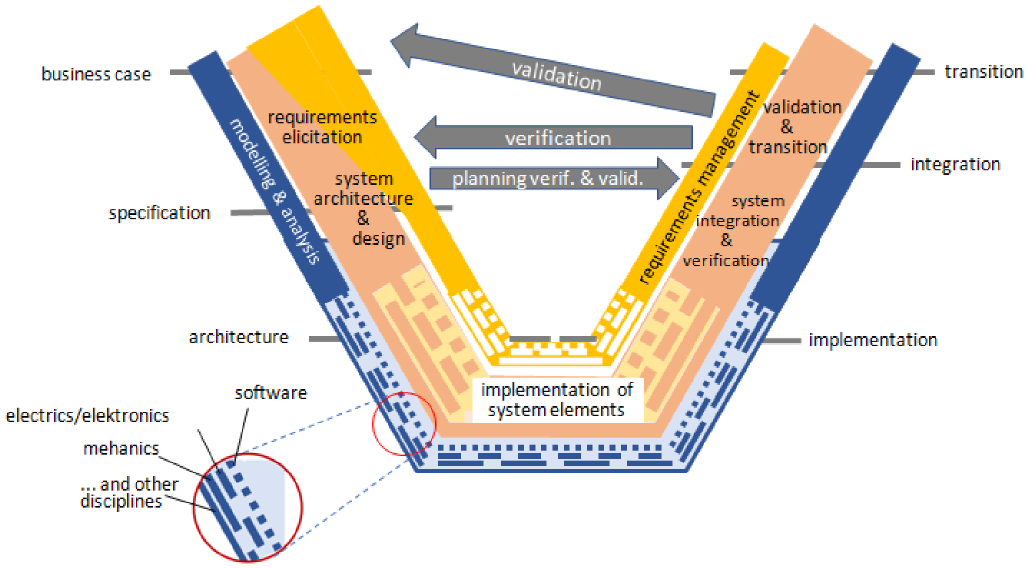

Fig. 1. The New V-Model proposed by I. Graessler and J. Hentze [5].

B. Description of Single Stages of Product Development

Requirements Elicitation

The organization, analysis, and fulfillment of predetermined needs are the fundamental requirements for a successful product development process. The new recommendations provide an extra tool: The main feature list for mechatronic and cyber-physical systems—to obtain a specification that is as comprehensive as feasible. Users are supported by this list of key factors in order to meet the requirements for completeness and quality [6]. Completeness, clarity, consistency, and performance of work functions are considered to be quality criteria for product specifications. During the development of a product, requirements are gradually added to and modified in response to consumer input and evolving needs.

System Architecture & Design

The system architecture and design phase is when the most significant transdisciplinary product engineering happens. The system architecture includes the fundamental mechanical structure, signal flow structure, and electronic circuit diagrams, as well as the structuring of the software program into its modules and components, including the appropriate interfaces, in accordance with the functional structure and the fundamental principles of work function.

The system architecture establishes the components, connections, and guiding principles for designing and further developing the system [5]. On the basis of understandable criteria, such as the recognition of interdependencies, functional analyses, and evaluation of exclusion criteria, structural options are contrasted. This process should ideally be coordinated with the intended user. Based on how the system is divided, an iterative process is used to discover the appropriate distribution of specific functions across different disciplines. It is practical to break the system down into separate functional components step by step in accordance with the system's ability to fulfill its intended function, as well as its dependability, simplicity, predictability, and adaptability.

Implementation of System Elements

The system's components are dimensioned, designed, and presented in detail before being put into use. Using suitable CAD software, Finite Element Methods (FEM), various calculation techniques, and simulations are used to dimension and design mechanical components. Modern calculating techniques are used in accordance with the available resource's criterion, or expected working life. In terms of load capacity, dependability, dynamic stability, and thermal stability, ideal structural solutions are selected. Suitable structural and technological documentation should be created for all parts, assemblies, and sub-assemblies.

For electrical and electronic components, printed circuit boards (PCB) are designed, application-specific integrated circuit (ASIC) are specified and field programmable gate arrays (FPGA) selected. Traditional PCBs are used to link components electrically and physically. Modern software systems (ECAD, FEM, FDTD, FIT) are used to design electrical equipment automatically. The development and selection of sensors, actuators, and the entire electrical infrastructure are all done in this phase.

Creating algorithms and software and then turning them into the required computer programs is how software parts are implemented. Algorithms are used to implement functions based on the software architecture, and related code is generated. Database models are put into practice by doing the proper modeling in accordance with predetermined plans. The design of user or system interfaces comes next. During detailed development, suitable mechanical, electronic, and software interfaces are considered. Obviously, many issues that arose during the system's integration must be resolved at this point.

System Integration & Verification

In this phase, the implemented elements of the system (mechanical elements, hardware, software, and provided services) are integrated into the next higher level of the product hierarchy with the aim that the complete system fully meets the expected requirements. Through appropriate simulations of virtual commissioning, a comprehensive examination of the functioning and mutual interaction of components or elements of the system is carried out.

During development, efforts are made to ensure the required performance of the product. Product characteristics are predicted at an early stage of product development, usually based on models. Checking the working characteristics of the product is carried out continuously through tests on virtual (computer simulation), physical prototypes (hardware experiment) or their combination. Therefore, the required working characteristics of the product are constantly checked in a virtual and/or physical environment. Verification should be done early on in the process of product development, and the outcomes must be exhaustive and quantifiable.

Validation & Transition

In this phase, the validation of individual elements and subsystems of the product should be performed. A check of the complete integrated system is required. Validation is performed in the presence of the user (customer or further user if the product is integrated into a more complex system). This validation must prove the appropriate quality of the product according to all requirements. All operating parameters must be checked and verified. It is most often performed on a prototype with appropriate simulation or real operating conditions. All the necessary models and documents for the next stages in the product life cycle are stored and structured using Product Data Management (PDM), which is part of the product development process. In this way, the final documentation of the product is completed. The basic models created in this phase enable the simulation of system behavior and are a prerequisite for creating a digital twin.

III. DIGITAL TECHNOLOGIES IN THE DEVELOPMENT OF SMART PRODUCTS

In particular, smart product development and intelligent manufacturing can be described as their combination with artificial intelligence [7, 8]. Except for artificial intelligence, smart technologies such as IoT, cloud computing, big data analytics, CPS, and digital twins are taking a central position in new-generation intelligent manufacturing [8, 9]. We are witnessing that there has been a shift from knowledge-based intelligent development to data-driven and knowledge-enabled smart manufacturing so that the term “smart” refers now to the creation and use of data [10].

A. Artificial Intelligence

In the centre of development of smart products and services, we can find different Artificial Intelligence tools. The best definition and assessment of importance of AI in modern industry is given by High Level Expert Group founded by European Commission in [11] and [12]: “Artificial intelligence (AI) systems are software (and possibly also hardware) systems designed by humans that, given a complex goal, act in the physical or digital dimension by perceiving their environment through data acquisition, interpreting the collected structured or unstructured data, reasoning on the knowledge, or processing the information, derived from this data and deciding the best action(s) to take to achieve the given goal. AI systems can either use symbolic rules or learn a numeric model, and they can also adapt their behavior by analyzing how the environment is affected by their previous actions. Like the steam engine or electricity in the past, AI is transforming our world, our society and our industry. Growth in computing power, availability of data, and progress in algorithms, have turned AI into one of the most strategic technologies of the 21st century. The stakes could not be higher. The way we approach AI will define the world we live in”.

Today's research in the field of artificial intelligence is mainly focused on the following tasks that smart products should perform:

- Perception - the ability of a smart system to interpret information from sensors in a way similar to how people use their senses to gain knowledge about the world around them.
- Knowledge representation – presenting information about the world in a form that the smart product can later use to solve complex problems.
- Reasoning and problem solving – generating logical conclusions and predictions from available knowledge.
- Machine learning - the ability to respond to changes by using existing knowledge to solve new and unknown problems.
- Natural Language Processing (NLP) – the ability to understand, interpret and manipulate natural human language.
- Robotics – the ability to move and manipulate objects from the environment.

These tasks can be achieved by using various means for the realization of artificial intelligence such as: search and optimization techniques, logical calculus, probabilistic methods for uncertain decision making, classifiers and statistical learning methods. In the recent years, different machine learning methods have been developed like: Linear and Logistic Regression, K-Nearest Neighbors, Decision Tree, Random Forest, Support Vector Machine, Naive Bayes. Among them, Neural Networks became most popular and most potent tool for solving various problems of classification and regression, especial in their multilayer form (deep learning).

B. Big Data and Analytics

The Cambridge dictionary defines Big Data as "very large sets of data that are produced by people using the internet, and that can only be stored, understood, and used with the help of special tools and methods" [13]. While it is true that the term Big Data refers to a vast amount of data that is constantly increasing, it does not mean that big data refers only to the volume of data. Indeed, implementing a big data strategy involves storing, analyzing, processing and tracking data. Therefore, numerous challenges arise, such as handling and visualizing data, integrating data from different data sources, securing data, etc.

In most business scenarios, the volume of data is too large, moves too quickly, or exceeds current processing capacity. So, it can be said that the problem with data today is actually the fact that there is too much of it, so we must put more efforts into finding the practical benefits from it. In that sense, a large amount of data is simply useless without software support to analyze it, because humans cannot do it efficiently. This is where AI comes into play, which gives better and better results because it has more and more data for training and evaluation. For this reason, big data and artificial intelligence are actually two complementary technologies.

Data has grown rapidly in practically every business and industry sector in recent years as a result of the Internet, Internet of Things, mobile applications, and cloud computing. These produced data are one of the greatest advantages for the development of new smart products and services [14]. Big Data's application in the development of smart products and services are separated into two directions: the first one is when we use Big Data for market analysis, and the second one is to use Big Data for product design itself.

Using analytics based on data from web click streams, social media content (tweets, blogs, wall postings, etc.), location data from mobile devices, data from the rendering of video footage, voice data from call centers or intelligence interventions etc., it can be concluded whether a product is needed, which functions and price it should have, which are the target groups, etc. The advantages discussed here are represented in developing better customer services, identifying potential new customers, identifying and developing new products and services, better-informed strategic direction, faster time to market, and lower costs.

These huge data collections can be also used for training and evaluation of different AI algorithms, and to implement in that way certain level of intelligence in data-based products and services. Having in mind that machine learning is the ability of computer systems to learn to make predictions from observations and data, it can be also used for predictive maintenance.

C. Internet and Sensing Technologies

Sensing technologies are another essential component of smart product development and operation modes of their work regimes. Sensing technologies, in combination with the power of the Internet, created another worldwide recognized and massively exploited technology – the Internet of Things. IoT represents a network of connected devices aiming to establish and facilitate communication between them on a local level or in a cloud [15]. The IoT exists to transform the physical world into a complex dynamic system of connected electronic devices. It is not only a technology that ensures the implementation of Industry 4.0. On the contrary, it effectively enables the improvement of an individual's daily life by contributing to the development of personal smart products.

The building blocks of every IoT solution are the following ones: sensing equipment, electrical circuits, embedded systems, internet and networking of devices. Sensors form the core of the IoT, and in addition to capacitive sensors, sensors can also be based on measuring resistance or inductance. Each of those cases' tasks is to measure real-world variables and transfer the measured numerical values to the central unit of the IoT system. In order to incorporate a large number of sensors within specific miniature IoT devices (smartwatches, embedded health devices), modern development tends to produce minimal sensors with high precision. Minimalist design has contributed to the development of IoT and has tremendous possibilities for future development attempts. The following figure shows a general block diagram of the building elements of an IoT system and the way of connecting the components from the power supply, through electrical circuits and processor unit, to sensors and actuators (Fig. 2). A typical IoT system has a local unit for managing the system's energy and a wireless transmitter that enables communication with other devices, the user portal, etc.

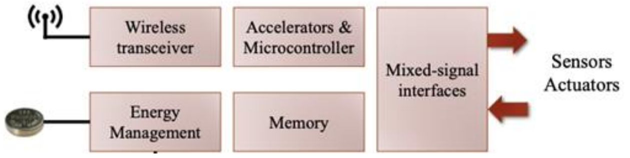

Fig. 2. Generic block diagram of IoT concept.

Another mentioned building block in the IoT ecosystem is an embedded system. The heart of embedded systems is a computer for specialized purposes, explicitly built and programmed for the purpose and narrowly profiled goals for which the system will be used. This means that if, for example, a new smartwatch model is realized, it will exclusively contain a narrowly profiled type of processor and computer components that will enable it to realize all the features that the watch should have.

IoT's value in smart product development lies in optimizing global manufacturing processes concerning performance, quality, costs and resource management [16]. It also allows the manufactured products to play a vital role in the development and design of the manufacturing process. Connected smart products powered with IoT technology can feed information back to the factory infrastructure so that potential issues can be detected and fixed during the production phase by adjusting product design or manufacturing processes. It's also helpful in gathering consumer feedback and answering their requests. From an application perspective, IoT and digital technologies are key drivers of digital transformation in various sectors. The future IoT will revolutionize how products and processes are organized and monitored in strategic value chains, giving European and worldwide industries the green and digital transition they need.

D. Digital Twin

Michael Grieves introduced 2002 the concept of the digital twin as part of his product lifecycle management. According to that, the digital twin represents a virtual image that contains all the information of a physical product and reflects it throughout the entire product lifecycle. This idea was so visionary that it could not be achieved for many years because computers were not powerful enough to bring the mentioned ideas to life [17].

It is a technology used in the industry to increase productivity by planning and optimizing the process of collecting and analyzing continuous streams of data coming from a real-physical asset and sent to its digital replica. Moreover, this technology in its essence has the main pillars of Industry 4.0, it is digitized, it is decentralized, it is modular and it allows working in real time to obtain the most adaptable and optimized results.

The digital twin reduces costs and increases efficiency and, most importantly, it always exists before the physical product. As Grieves said [17] “*I would like to develop a product virtually, test it virtually, create it virtually, and support it virtually. And only if the virtual product is successful in these ways will I make the physical product and put it to work*.”

The digital twin emphasizes a two-way approach. It has a fully automated flow of data between digital and physical objects (Fig. 3). This approach means that changes in the state of the physical object lead to changes in the digital object and vice versa. A digital twin is a process and not an object. In data-driven engineering, the digital twin plays a central role as the dynamic hub where information and all data related to the creation, building, and exploitation evolves.

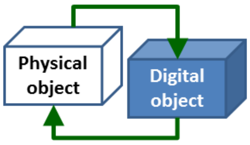

Fig. 3. Digital twin model.

The most important step is to create high-fidelity virtual models to realistically reproduce the geometries, physical properties, behaviors, and rules of the physical world [18].

Within the cyber-physical system of a functional digital twin, data exchange is also a two-way process. Namely, data from the factory level could be sent to the digital twin and it can also send data to systems on the factory level to initiate specific actions.

There are numerous areas of application in the manufacturing domain of the digital twin concept. This concept that can be utilized in a variety of ways throughout the systems’ lifecycle is described in detail in [19]. Three categories for use cases can be identify here [20]: *monitoring* (e.g., health assessment), *mirroring the systems’ life* (e.g., lifecycle management), and *decision support* (e.g., modeling, visualization, simulation, optimization).

IV. CONLUSIONS

According to the guidelines for I4.0, the most important activity for its successful implementation is the development of smart products. In that segment, all product parameters are defined, whose task is to reliably perform the intended work function in complex operating conditions. This implies that they have appropriate autonomy with a built-in degree of intelligence that permanently monitors the state of working order through appropriate systems, reacts to sudden emergency situations, and restores the system to working condition. In order to fulfill these, it is necessary to apply adequate engineering in the process of developing and designing smart products.

The paper presents a new V-model for the development of smart products, which has a holistic approach and is based on the principle of interdisciplinary system architecture, which enables the synchronized development of mechanical, electronic and software components with appropriate integration, validation and verification. In all phases of this model, the paper shows the place and role of the application of digital technologies. The basic characteristics of the artificial intelligence model, big data and analytics, internet and sensing technologies and digital twin were analyzed in order to see the possibility of their flexible integration into the standards of new technologies of smart product solutions.

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