Towards a DevOps Approach in Cyber Physical Production Systems Using Digital Twins

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Abstract. Nowadays product manufacturing must respond to mass customisation of products in order to meet the global market needs. This requires an agile and dynamic production process to be competitive in the market. Consequently, the need of factory digitalisation arises with the introduction of Industry 4.0. One example of the digitalisation is the digital twin. Digital twin enhances flexibility due to its adaptability and seamless interaction between the physical system and its virtual model. Furthermore, it bridges the gap between development and operations through the whole product life cycle. Therefore, digital twin can be an enabler for the DevOps application in cyber physical production systems as DevOps aims at merging Development and Operations to provide a continuous and an agile process. This paper analyses the use of the digital twin to enable a DevOps approach of cyber physical production systems (CPPS) in order to create a fully integrated and automated production process, enabling continuous improvement.

Keywords: Digital twin · DevOps · Life cycle · Cyber physical production system

1 Introduction

The manufacturing sector is continuously facing the rapidly changing market needs. In fact, product manufacturing complexity is increasing as the market requires more flexible, reconfigurable and customised systems that are capable of adapting to changes throughout the whole product life cycle. This emerges the need of new approaches and technologies in order to decrease the development cost and time, improving efficiency and effectiveness. Digitalisation and Industry 4.0 are the technologies emerging to face these challenges with the transformation of the manufacturing process into a fully digital and intelligent process where automation plays a key role [17]. The digitalisation of the industry makes a step forward towards the automation, integration and optimisation of the production process and it enables operation and monitoring throughout the whole product life cycle.

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In this paper, we focus on digitisation as an enabler of the continuous improvement during the product life cycle. In this sense, digital twins are emerging as the latest trend on digital transformation. This technology links the physical asset and its virtual model in an agile and continuously evolving environment. The digital twin gives the possibility to continuously improve the model by 1) collecting real time data and analysing it in order to foresee malfunctions and 2) introducing improvements on the product and validating them in a virtual environment before deploying them into the real system. In addition, the digital twin has the ability to adapt its model seamlessly and near real time as changes are made on the system, thus facilitating the production flow. All these characteristics and capabilities of the digital twin accelerate the integration of an agile and continuous production process, principles of the so called DevOps approach.

DevOps approaches are being used widely in software development, specially for web-based applications, delivering faster applications and continuously. In fact, it has been mainly used to automate the development and deployment of web based applications from end to end [10]. DevOps is a continuation of the Agile journey [15] (often referred to continuous delivery, integration and deployment) that merges the development and operation with cross-functional collaboration process. A DevOps approach on software development brings these agile principles for continuous software development and deployment.

In other types of development, such as manufacturing systems and cyber physical production systems (CPPS), there are still some challenges that need to be addressed. These systems must deal with legacy architecture and hardware limitations in order to integrate a flexible and adaptive environment. In any case, the manufacturing sector could benefit from a DevOps approach to create a continuous production system and bring continuous improvement throught the whole product life cycle. However, adoption of DevOps in the manufacturing sector requires an agile and adaptive system where digitalisation is one of the key elements and the digital twin the main enabler.

This paper analyses the use of the digital twin for a DevOps approach on CPPS. The digital twin technology enables DevOps to develop and test the product simultaneously, reducing development costs and time to market. Moreover, the bridge between development and operations guarantees the continuous improvement in an agile environment.

The paper is structured as follows: Sect. 2 introduces briefly the background of the digital twin, DevOps and Cyber Physical Production Systems, and on the other hand, it highlights the motivation of the paper. Section 3 describes the digital twin for a DevOps approach on product manufacturing of CPPS. Finally, Sect. 4 provides the conclusions and future work.

2 Background and Motivation

2.1 Digital Twin

The digital twin has its origin in 2003, conceived by Grieves with the product life cycle management [13]. However, the term digital twin was firstly defined by NASA in 2010 [27] as follows "A digital twin is an integrated multi-physics, multi-scale, probabilistic simulation of a vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its flying twin." Nowadays, there exists a wide range of definitions, therefore, it is necessary to clarify the concept. From the author's perspective on product manufacturing, the digital twin is the virtual representation of the physical asset where both counterparts are connected to each other and are dynamically updating through the whole product life cycle [21,25].

The digital twin model requires a physical entity, a virtual model and connected data [21,25]. However, Tao et al. proposed the five-dimensional Digital Twin (see Fig. 1), composed of a physical entity, virtual model, digital twin data, services and connections [26,30].

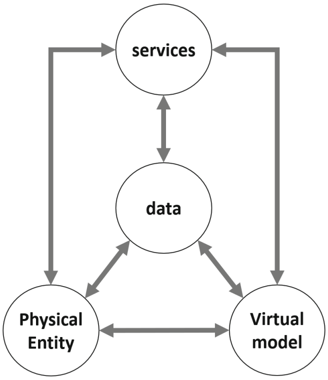

Fig. 1. Five dimensional digital twin - adapted from [30].

2.2 DevOps

DevOps aims to bridge the gap between software Development (Dev) and Operations (Ops) by combining best practices from both domains and enabling collaboration between the teams [4]. The main principles of DevOps are focused on continuous integration, continuous delivery and continuous deployment [15] as depicted in Fig. 2.

Continuous Integration: Continuous integration (CI) is a principle that puts a great emphasis on the dynamic software integration process and test automation [5] in order to detect problems easily early in the process. It is a prerequisite for continuous delivery [15].

Continuous Delivery: Continuous delivery (CD) aims at delivering new software features with greater speed and frequency [5]. This requires the software to be always ready for release [11] and promotes the automation of the release process, enabling a constant flow.

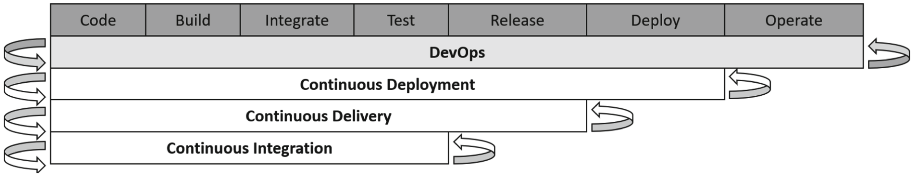

Fig. 2. DevOps principles through the software life cycle.

Continuous Deployment: Continuous deployment is usually confused with continuous delivery, however it goes a step further. Every change that is successfully committed on the previous stages is automatically deployed to production [11].

DevOps benefits from these principles to shorten time to market, reduce development costs and increase productivity with a higher quality. Moreover, it goes beyond by covering the entire life cycle, from development to operations.

2.3 Cyber Physical Production Systems

Cyber physical production systems are formed by different CPS, comprising different elements and sub-systems connected to each other autonomously and in cooperation [23]. The main objectives that a CPPS should meet are the following according to Monostori et al. [24]:

- Responsiveness to any changes in the system or environment.
- Intelligence of the components that are part of a CPPS.
- Connectivity between the elements, services, subsystems and other systems.

Therefore, the digital twin represents a fundamental prerequisite of cyber physical production systems due to its adaptive ability, real time and seamless connectivity and control of the production process.

Regarding the development of CPPS, this implies system verification and validation before releasing it into operations. System verification is often carried out in silos by each engineering discipline and thus, different interdisciplinary simulation tools are utilised for partial simulations. Consequently, the final product is not jointly validated until the system is fully integrated and interoperability issues become a major challenge. Thus, there exists the need to carry out interdisciplinary tests in a jointly environment from early stages of the development.

2.4 Motivation

DevOps practices are mostly applied to software development and little has been done on cyber physical systems. Nevertheless, Garcia and Cabot applied DevOps practices at the model level for the very first time in 2018 [11] and it has been explored to model driven engineering in cyber physical systems in the recent years [6,33].

DevOps life cycle is not only applicable to software development and its cycle changes based on the applicable environment. Implementing DevOps principles at the entire life cycle of model based approaches is the next step of cyber physical systems, enabling a continuous and dynamic life cycle of the system. However, cyber physical systems must overcome the following barriers to integrate a DevOps approach [6,12]:

- Dealing with hardware constraints due to different communication protocols, programming environments and dedicated hardware.
- Real time communication between the physical and virtual systems.
- Obtaining feedback data from operations, customers and other systems.
- Facilitating a collaborative framework between different stakeholders and engineering disciplines.
- Supporting an agile and a flexible environment.

This paper puts forward the use of the digital twin in order to carry out a DevOps approach into CPPS. The digital twin technology facilitates a flexible environment with the dynamic adaption capability of the physical asset and its virtual counterpart. In fact, both counterparts are continuously adjusting to the changes in real time. On the other hand, this technology enables interdisciplinary collaboration so that operations and development can co-work together and get mutual feedback through the whole life cycle.

3 Digital Twin as DevOps Enabler for CPPS

The digital twin brings an agile framework for the development and operation of cyber physical systems [36]. Therefore, the authors introduce the digital twin as a DevOps accelerator where it stages a DevOps approach throughout the whole product life cycle. This way, product design, engineering, integration, operation and service activities can be performed efficiently on an agile and collaborative environment between different departments [3] and engineering disciplines such as mechanical, electrical and automation, among others.

Figure 3 represents the digital twin as the enabler of DevOps across the product life cycle of a CPPS. In this case, the digital twin is the technology to shorten the gap between the development and operations as it interchanges data seamlessly through the whole life cycle. This way, the development process benefits from the feedback obtained from the operational data and vice versa.

The following subsections describe the use of the digital twin within the development and operations of a CPPS and highlights DevOps practices in order to achieve a continuous and runtime production system.

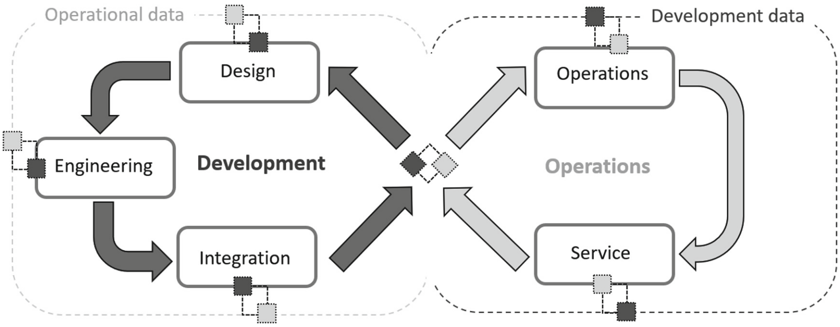

Fig. 3. Use of the digital twin for a DevOps approach across the product life cycle - inspired by [3,32].

3.1 Digital Twin in Development

The development process involves the design, engineering, and integration phases, and requires testing practices for the verification and validation of the model before being released. Model Verification and Validation, V&V, determines if the model is correct by the verification of the model, and on the other hand, it validates that the requirements are met successfully and that the model is adequate to represent the real system. Tania Tudorache proposed the V model for a mechatronic product development process in 2006 [32]. A decade later, in 2018, the use of the digital twin for V&V was introduced by Dahmen et al. as simulation based verification with experimentable digital twins [7,8].

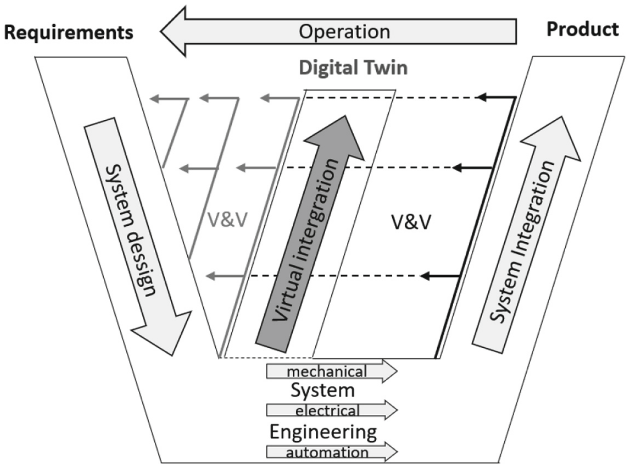

Fig. 4. V model for continuous product development process - adapted from [32].

The V-model of a traditional mechatronical system [32] verifies and validates the system during the last step of the product development process, it does not allow to perform V&V before the system is integrated. This arises system design and engineering problems during the integration stage, making its resolution difficult and increasing development costs and time to market. To confront this, there exists simulation tools that carry out partial system verification of each engineering discipline. However, carrying out simulations solely derive into interoperability issues between these interdisciplinary models during the system integration. Therefore, the V model is adjusted to integrate the digital twin practices from the experimentable digital twin [8] and thus, enable system verification and validation from the initial phase of the development process (system design) as seen in Fig. 4. The digital twin provides a new stage called virtual integration where the physical components are replaced by their virtual models before building the actual system. Moreover, a DevOps approach has been applied to the V model in order to gain insights from operations and provide a continuous product development process.

One of the applications that encompasses the whole V&V model is virtual commissioning. Virtual Commissioning is performed by the use of virtualisation and simulation technologies (such as the digital twin) in order to perform a series of collaborative verification tasks between domain specific engineering disciplines and through the whole development process (system design, system engineering, system integration or commissioning).

The main objectives of the use of the digital twin in product development process are described below [20]:

- To reduce time to market.
- To reduce development costs.
- To improve the performance of the production line.
- To reduce the failure rate and downtime of the production line.
- To solve interoperability issues between different domain tools and systems.
- To detect design and engineering errors, failures or malfunctions at earlier stages of the development process.

System Design. Designing is the first phase going down on the left side of the V model. It starts from the system requirements and describes the main physical and logical operation characteristics of the product [32]. System validation and verification must be accomplished in order to meet the requirements and this is facilitated with the digital twin as it permits testing the designed model by replacing the required physical components with their virtual models. Moreover, the digital twin provides feedback and the knowledge gained from the operational data for continuous design improvement [3].

A practical use case of the system design is the optimisation of the product. For example, Soderberg et al. applied the digital twin on design optimisation in order to obtain good geometrical quality in the final product [28].

System Engineering. System engineering is the phase following the system design up to the integration phase. An interdisciplinary approach is applied to the system design by adding domain specific engineering functionalities (mechanical, electrical, automation, etc.) to the model [32]. Traditionally, the engineering development was carried out in silos with multiple domain specific models, however, the digital twin sets up a collaborative framework where all disciplines can co-work in the same environment. Moreover, the use of the digital twin permits carrying out what-if simulations and making changes on the virtual environment before the real system is released. It also facilitates the testing of specific functionalities on a secure environment, for example Bitton et al. created a cost effective digital twin to facilitate the security evaluation of a specific industrial environment [2].

System Integration. The last phase of the V model is system integration. This is a critical phase as the engineering models, system components and interconnections are brought together [32]. Traditionally, the validation and verification of the system was carried out when the system integration was completed, thereby, unexpected errors were frequently arised due to dependency of the previous phases (design, engineering). However, the system can be tested before the real system is built with the use of the virtual models and digital twins (e.g. virtual commissioning technology). Therefore, the digital twin permits a flexible environment for continuous integration as it facilities testing the system securely on the virtual environment and it can then be automatically deployed to the real system. Another practice is the assembly commissioning process optimisation in order to improve the assembly quality and efficiency [29].

3.2 Digital Twin in Operations

Once the development process is completed, the product is realised into operations and service, closing the loop of DevOps.

Operations. The system is running on a real environment and runtime verification and validation of the system can be accomplished [14]. Operational data of the physical system can be used as input to the operational digital twin for predictions of breakdowns or failures, and vice-versa, knowledge gained on the operational digital twin can fed back to the physical asset for continuous improvement within the development process. Some of the operational applications and real use cases of the digital twin are described below:

- Optimisation of the system operation [19].
- Decision making under unexpected situations: runtime controllability verification of a control command [14], optimal state control framework [34], controllability of the physical layer [35], holistic online parallel controlling [19].
- Reconfiguration of the manufacturing system for reacting on changeover of the product order [18].

Service. Lastly, the service stage provides real time status and monitoring of the product, closing the loop of the operational cycle. In this scenario, dynamic data obtained from the physical asset (usage, wear, temperature, etc.) is mapped to the operational digital twin for real time monitoring. Furthermore, the historical data and the knowledge retrieved from the development cycle is combined with current operational data in order to carry out preventive maintenance. Thus, most of the services are related to real time monitoring, asset management and educational purposes:

- Monitoring: continuous monitoring [19,35], real time monitoring to improve the product quality and production efficiency of a welding production line, real time status warning of the production process [36].
- Real-time transmission of manufacturing updates [1].
- Tracking and updating warehouse inventory [1].
- Maximum traceability and transparency for the supply chain [22].
- Training and learning: learning environment for engineering education [31], a versatile learning environment to facilitate collaboration between industry and academia [16].

4 Conclusions and Future Work

In this paper we have discussed the use of the digital twin as the main enabler to apply a DevOps approach in Cyber Phsycal Production Systems. The digital twin is the bridge between the physical and real world, and also between the operational and development life cycles of a CPPS. Digital twin makes a step forward towards DevOps due to its agile framework for a continuous production system.

The digital twin provides current operational production data converging it with the synthetic data of the virtual model. This creates a runtime production development process as it gains insights and new requirements from operations in order to make adjustments on the go, by providing a proactive and a continuous optimisation process. A continuous production system could made a shift in virtual commissioning.

Furthermore, virtual commissioning practices are usually proceeded in silos between different domains of engineering (mechanic, electronic, automation) where seamless interaction between these interdisciplinary models is a challenge when testing the whole system. In contrary, the digital twin brings the collaboration between all these disciplines and models in the same environment, hence avoiding interoperability issues.

Beside all the benefits that the use of the digital twin and a DevOps approach would bring to the manufacturing sector, there is actually a lack a of industrial practices. One of the main challenges is the lack of standards for digital representation. In this sense, the Asset Administration Shell (AAS) is a promising standard for the digital twin representation as it holds properties, models and functionalities of all the components part of the system [9]. Nevertheless, it is still not a mature standard and its implementation into CPPS should be the way forward.

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