Using digital twin for maintenance applications in manufacturing: State of the Art and Gap analysis

Panagiotis Aivaliotis
Laboratory for Manufacturing Systems & Automation
University of Patras
Rion Patras, 26504, Greece
paival@lms.mech.upatras.gr

Konstantinos Georgoulias
Laboratory for Manufacturing Systems & Automation
University of Patras
Rion Patras, 26504, Greece
kgeo@lms.mech.upatras.gr

Kosmas Alexopoulos
Laboratory for Manufacturing Systems & Automation
University of Patras
Rion Patras, 26504, Greece
alexokos@lms.mech.upatras.gr

***Abstract*—The digital twin concept is more and more appearing in industrial applications including the field of the predictive maintenance. This paper, initially, summarizes and presents studies that use the digital twin concept for digital twin concept for condition monitoring and predictive in manufacturing. Following, the gaps in the existing literature are identified and analyzed and a brief proposition of the way that the already existing state of the art can go further is presented. A future outlook of the research in the particular field is provided.**

Keywords— Digital Twin, Predictive Maintenance

I. INTRODUCTION

The term Digital Twin (DT) can be described as a digital copy of a real factory, a machine, a worker and more, which is created and can be independently expanded, automatically updated besides being globally available in real time. The Digital Twin concept model contains three main parts: a) physical objects in Real Space, b) virtual objects in virtual space, and c) the connections of data and information that ties the virtual and real products together [1]. An indicative concept of achieving the digital twin is depicted in Figure 1. The, in some cases real-time, data gathering/monitoring and the updating of the digital model, aims at having the same behavior of the virtual model of as that of the real object (e.g. a machine).

If the DT was to be applied in real industrial practice, then every real product and production site would be permanently accompanied by a digital twin. Essential to the digital twin is its ability to consistently provide all subsystems with the latest state of all required information, methods and algorithms [2].

Remaining Useful Life (RUL) is the remaining operative capability of an asset during time [3][4][5] and there are several methodologies available to calculate the RUL of subsystems and components, enabled by various techniques. The calculation of RUL enables the implementation of predictive maintenance strategies. The Digital Twin concept enables the creation of predictive maintenance strategies, based on the digital representation of a machine or a group of machines. Using digital twin technology, the maintenance strategies could pass from the reactive to the predictive behavior. The predictive maintenance strategies, in contrast to the reactive ones, are condition-based approaches. It means that a set of indicators, which are estimated through data from the production line, are used like a warning mechanism for the upcoming breakdowns or failures of a machine.

One very important added value of using a digital twin for predictive maintenance is that a set simulation can be performed on the digital model of the machine, aiming at revealing aspects, such as component degradation of the real machine, that cannot be directly identified by using information only collected by the real machine components. This approach also avoids stoppages the real machine's operation in the production for testing. The engineers/users have the ability to simulate the future operations of the machine, to create failures profiles and even to plan the maintenance activities, based on the digital twin simulation results.

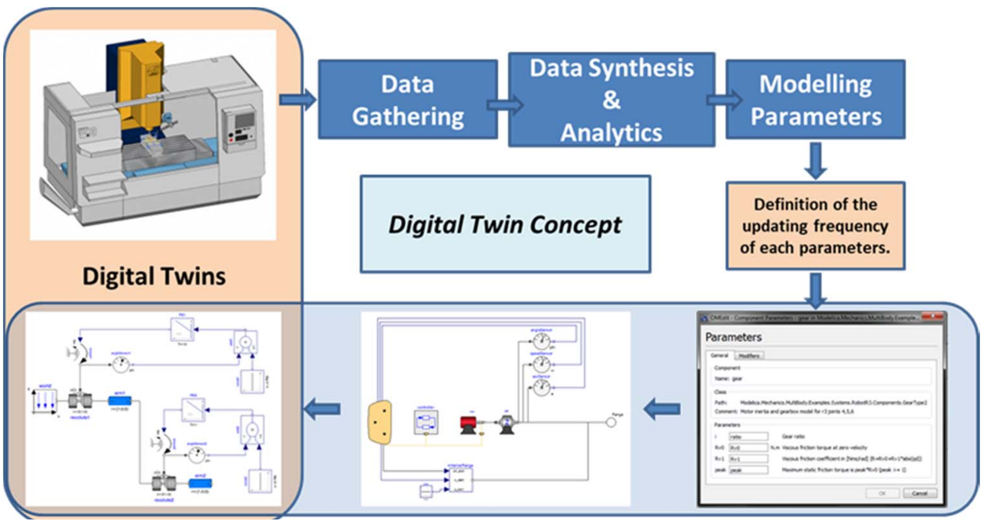

Fig. 1: Digital Twin concept

The scope of this paper is to present a literature review, regarding the digital twin concept of predictive maintenance strategies.

Additionally, the available tools, which have the capabilities to create and implement digital twin models, are presented below. A gap identification analysis will also be done, for what is missing and the way of dealing with it.

More specifically, Section 2 describes the research statement. Section 3, includes a detailed literature review for the digital concept and its integration with maintenance strategies. In Section 4, gap identification takes place. Finally, in Section 5, there is a presentation of this paper's outcome and the researchers' future activities.

II. Research Statement

As it is aforementioned in the Section 1, the main objective of this paper is to present the already existing implementation of the digital twin concept in the field of maintenance and health prediction based on the literature. More specifically, the paper aims to answer the following research question: "How Digital Twin concept can be used in the field of maintenance and health prediction?".

To answer the research question, a literature review took place. The authors have searched in two main sources in order to identify the already existing approaches; the ScienceDirect Database and the Scopus Database. All the types of publication, including books, conferences' papers and journals, are taken under consideration. Regarding the time horizon, all the papers have been published between 2010 and 2017 with some exceptations. The main reason of this limitation is that Digital Twin technology is appeared with the coming of Industry 4.0 which arise mainly after 2010.

III. Literature Review

The advancements in computer technology have enabled the establishment of increasingly sophisticated virtual models of physical artefacts as well as the fusion of such models for systems engineering [6]. Following this baseline, the digital models are used for two main reasons. Firstly, the models are used to serving the design verification and validation [7] and secondly, as the master product model, comprising the model-based definition of required product characteristics [8]. Taking under consideration their evolvement in IoT technologies, the modern smart products are able to interact with the virtual models and to provide them with information about their operating conditions [9].

Model-based Maintenance is discussed in terms of inspection, monitoring, diagnosis and planning, based on functional, behavioral and state models. Faults and deterioration of mechanisms can be described using Function-Behaviour-State modelling, in terms of user perception and measurable quantities [10]. In another research, prognostic models are constructed on the basis of different random load conditions. The hidden damage of a component is estimated with the use of an interacting multiple model (IMM). Finally, the remaining life estimation is performed by mixing mode-based life predictions via time-averaged mode probabilities [11]. In another paper, the researchers have focused on the intelligent diagnosis, using hybrid model-based techniques that seamlessly employ quantitative models and graph-based dependency models. According to this research, automotive engineers have found quantitative simulation to be a vital tool in the development of advanced control systems [12].

The fist definition of the digital twin was forged by NASA as "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 [13][14]. Aerospace researchers have started referring to the said NASA roadmap as the seminal work to define the DT [15]. Stochasticity, historical data and sensor data have been taken under consideration, aiming to achieve the interaction of the vehicle with the real world. In the same baseline, research starts to be done with use of digital models for life-cycle viewing [16], checking on mission requirements [16,17] and for prognostics and diagnostics activities [14]. Some of this research is analyzed below.

In [16], an Airframe Digital Twin was used for the performance of computational simulations, aiming to provide a forecast of future maintenance needs of an individual aircraft. The high-performance computing enables the use of the Digital Twin concept according to the paper. The Airframe Digital Twin was envisioned to be an ultra-realistic, cradle-to-grave computer model of an aircraft structure. According to [17], the Airframe Digital Twin will virtually take each flight that the physical aircraft makes in order for the loading and subsequent damage to be determined. Another paper discusses a rational engineering approach to real-time "tail number" prognosis of composite structures, based on the measurement and science-based interpretation of changes in multi-physical material properties [18]. In paper [21], the adaptability of a RFLP framework to a Systems Engineering Methodologies is demonstrated, while taking profit of PLM values for the production of industrial systems. The result of combining the architectural design with PLM, increases the likelihood of detecting product failures early on during its lifecycle.

In [19], they have combined the recent developments in modeling fatigue-damage, the isogeometric analysis of thin-shell structures, and the structural health monitoring in order to develop a computational steering framework for fatigue-damage prediction in foil-scale laminated composite structures. AutomationML has been used to model attributes, related to the Digital Twin for metrology work, too [20].

Although, AutomationML supports definition data such as geometry, kinematics, control logic, communication and topology, it lacks description of mechatronic process models, describing physical behavior of factory equipment. A preliminary research effort that applies basic principles of this concept has been developed and tested in an anomaly detection pilot case in a laboratory setting [22]. Virtual Commissioning (VC) methodology provides a solution to the verification of mechanical behaviour of a line and a cell, in conjunction with control logic units such as Programmable Logical Controllers (PLCs) in loop with a virtual environment. Applying VC technology can reduce up to 75% of real commissioning time as reported in Park et. al (2011) [23]. Makris et. al. (2012) presents the application of VC to the case of an industrial robotic cell, involving cooperating robots for automotive body in white application [24]. However, in that case no feedback loop from the production environment for speeding up production system control model development process has been proposed. The generation of simulation models based on plant engineering data, usable for VC is presented also here [25]. Simulation platforms that are available for VC are among others, SIEMENS SIMIT [26], Delmia Automation [27], XCELGO [28], SimulationX [29] etc. Dymola from CATIA systems offers also simulation of complex systems for different industrial sectors, focused on the simulation of dynamic behaviour and interactions between multiple systems. An open source system also is offered for simulation online is also GAZEBO [30] offering an interface to ROS platform. Despite that fact, the maturity of such systems and ROS are not enough for being stable in the industrial environment. Promising approaches for the future remain the virtual twin and the co-simulation. In [34], the use of digital world modelling techniques in hybrid production systems for enabling system reconfiguration through shared environment and process perception is investigated. In the same way, the digital twin concept has been implemented to enable the safe human robot collaboration [33]. In [35], an implementation of the digital twin approach as part of a wider cyber-physical system (CPS) to enable the optimization of the planning and commissioning of human-based production processes using simulation-based approaches has been analyzed.

An approach to the way of implementing the digital twin concept for predictive maintenance has been presented in another paper. The resources of the production plant are modelled in order to enable the simulation of their functionalities. A smart control system is developed, aiming to gather machine data, both from the machine controller and the external sensors, before providing them as input to the simulation tool. The outcome of the digital twin simulation is the prediction of the machine's health status, which then, is used for the identification of the machine's maintenance activities. Efficient algorithms and technologies for data analysis and prediction are utilized. In this way, the condition and the status of the machines can be predicted as a result from the simulation of physically-based digital twin models, without the machines' operation being stopped, as it happens in the common predictive maintenance solutions [31].

In the same way, another research presents an approach to the use of digital twin models in a cloud prediction layer, aiming to identify the machine health status for a long-time period.

Specifically, some data will be gathered by the machines' controllers and external sensors, which will be structured and uploaded to a cloud database. Some of this data will be used for the simulation of the digital models, while some others, will be used to update the simulation models, aiming to ensure that the simulated functionalities of the machines will be the same as those of the real one. Therefore, a digital twin of the real production equipment will be created. Finally, the upcoming process plan of the machine will make up for the input of the simulation model. The output of the simulation, in combination with the reliability parameters of the machines and the real time monitored data, will be used for the final RUL calculation [32]. The proposed methodology is depicted in Figure 2.

IV. Gaps Identification & Potential Actions

Based on the literature review, it seems that considerable research deals with the challenge of maintenance and life prediction by using the digital twin model. However, a general platform based on the creation of a physical model via a common methodology, is still missing. There is not any common line for the development and implementation of the digital twin concept. This is a requirement for the implementation of the digital twin concept for maintenance. More specifically, the implementation of the digital twin technology, for maintenance activities in a production plant, requires the creation of the digital model for each machine. Due to the great variety of machines included in a production plant, a common framework for the creation of the digital twin, using specific tools, should be defined.

The fact that nowadays, the main characteristic of the machines is their high complexity, a common framework to help all the users, in different industrial sectors, should be created.

Particularly, a model creation methodology should be defined aiming initially to help the users create simple digital models and then, to support them in completing their high complexity model.

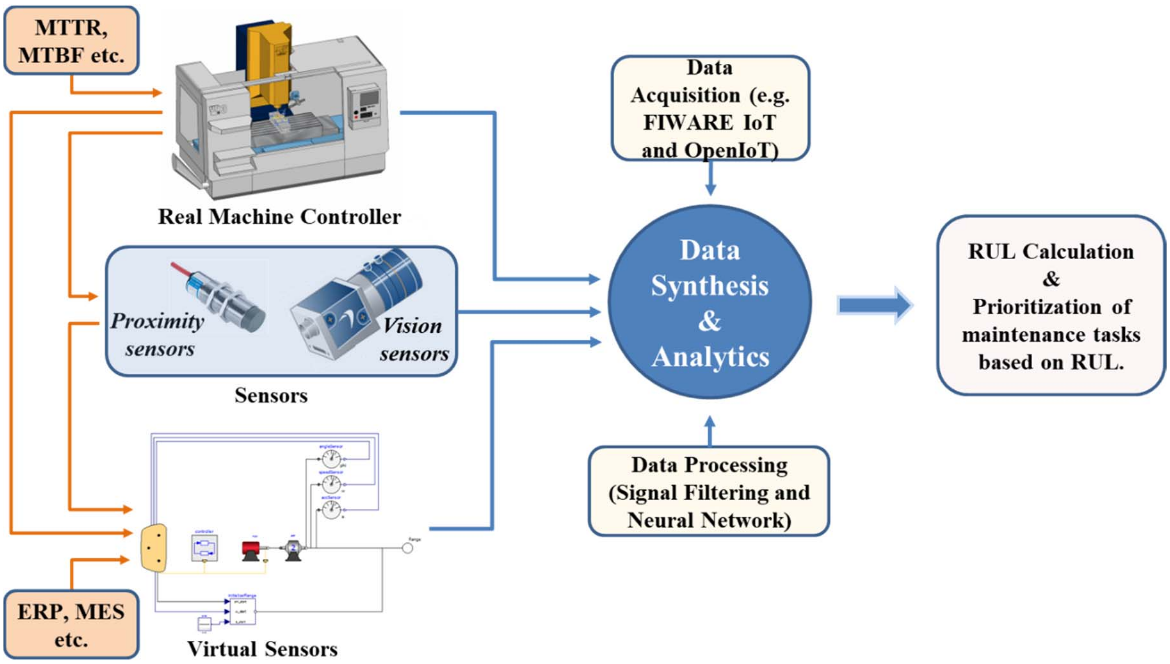

Fig. 2: RUL calculation main concept using Digital Twin [32]

This advanced modeling methodology for digital twin should consist of discrete steps for the model's creation. A very brief approach could comprise a first phase in which both the kinematic and the dynamic behavior of the machine will be modelled. The selection of the machines' components that will be modelled should be identified on the basis of the data being available for each one of them. Their categorization in white, grey or black box models should take place. Then, the input of the model should be specified, depending on the available real data, which will be monitored and will be provided to the model for simulation. Next, a set of parameters will be identified by being updated online, via real data available and aiming to keep the digital model updated and to achieve the digital twin concept. The selection of the updating parameters should be made through a number of rules to prevent the creation of high computational time models.

Furthermore, a simulation tuning mechanism should be developed capable of being adapted to a majority of digital models thus facilitating the digital twin concept as it was mentioned above. The monitored data should be translated into information in order to be used as input to a synchronous simulation tuning tool. A data synthesis technique will also be utilized after having taken under consideration both the physical and the computational reductions. The synthesized data target at tuning the models via the updating of the modelling parameters. Furthermore, some of the modelling parameters will be tuned with lower frequencies than others because of their lower effect on the simulation process. A weight factor table defines the frequency of tuning for each machine's component. In this way, the computational time is reduced.

The novelty of the proposed advanced modelling methodology and simulation tuning mechanism is their versatility, it means that they can be utilized from the user to enable the digital twin concept for any kind of machinery.

V. Conclusions

The scope of this paper is to present existing research, which deals with the digital twin concept and the way it is implemented for maintenance activities. In addition, an analysis and the identification of the gaps in the literature have taken place. The main gap identified is the missing of a common framework to support the users in creating digital twin models. Although a number of commercial simulation frameworks are in the market, there is not a common methodology capable of being adapted to the modelling of the majority of the machines/mechanisms. In the same way, what is still missing is a methodology of an updating mechanism, which will be able to connect the digital models with the real machine data and to adjust the models' parameters, aiming to achieve the digital twin concept. Common methodologies for the creation of a digital twin model constitute a requirement for their implementation of condition-based maintenance. The creation of common methodologies is very critical for the use of the digital twin technology for the prediction of the machines' health status, since there is huge variability among the machines of a production plant.

An approach to going beyond the state of the art is briefly presented in the paper. Specifically, a number of steps should be followed in order for the digital model to be built. Regarding the tuning of the models, a number of updating parameters should be selected aiming to be updated through real data and thus, to adjust the behavior of the digital model according to the real machine's behavior. The expected impact of the proposed approach in a real context will be that the user can be able to use a common strategy to enable the digital twin concept for a number of different machinery.

Our future study will focus on developing a framework, which will support the users in creating a digital model, in terms of the digital twin technology as well as a synchronous simulation mechanism, aiming to be used by predictive maintenance strategies. A short description of the proposed approach was analyzed above. Finally, a more detailed literature review should also take place for the identification of more gaps, which will be addressed in the proposed model creation and tuning framework.

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