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# A review on simulation in digital twin for aerospace, manufacturing and robotics

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ABSTRACT

The Digital Twin (DT) is known as a computer-generated equivalent of a physical system. It is used to simulates for different objectives through the real-time harmonization of data received from the field. The prime interpretation of DT is very close link to simulation technique and software used. This relation can be viewed in two approaches viz., (i) DT is model to present the system based upon the various kinds of simulations techniques and tools and, (ii) DT as simulation of the system itself. In the aerospace, simulations replicate the continuous time history of flights, producing vast amount of data of simulations in order to recognize what the aircraft has undergone and to project forthcoming maintenance requirements and intrusions using various applications based simulation techniques, Computational Fluid Dynamics (CFD), Computer-Aided Engineering (CAE), Finite Element Methods (FEM) and Monte Carlo simulation. In case of manufacturing, the simulation helps to mimic the complex behavior of production procedures considering the effects of design constraints, human interventions, and any other external disturbances. In robotics, the simulation is mainly concern with the virtual commissioning of task in order to improve the control algorithms for robots in the course of development stage. In this paper, various recent contributions on simulation-based DT and DT-based simulation models proposed by researchers in the field of aerospace, manufacturing and robotics have been presented. The motivation behind this review is to pave the way and clarify the conceptual foundations on the adaptation of simulation techniques and software to develop DT for various applications.



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## 1. Introduction

As per the Business Directory, digitization is an ‘‘*Integration of digital technologies into everyday life by the digitization of everything that can be digitized*”. In an industrial context, it is the increase in creation, use and storage of digital things in the life cycle of products and systems. These digital things possess a complete data and information which is required by various investors as well as it create a massive storage of digital data. In fact, the computational power has been increased drastically and it is readily available throughout the world. Owing to this, the simulation technique has been empowered to solve more complex problems, integrate the models of different designs and accurately predict the behavior of systems. These high-level simulations are normally termed as a Digital Twin (DT) corresponding to the system they modeled. DT is not merely a large collection of all digital things; it is having a well-structured architecture and the entire components are linked as well as it has metainformation and semantics [19]. In fact, the DT is the cutting-edge approach for modeling, optimization, and simulation.

During 1960s, the simulation was limited to very specific topics by experts such as mechanic. After 1985, the simulation was used as basic and standard tools in order to resolve some specific design and engineering problems, for instance fluid dynamics. Subsequently, the simulation-based system design was started around 2000 onwards in which simulation is a general methodology for ‘‘*multi-level and multi-disciplinary systems*” having greater functional varieties and applications, for example ‘‘*Model Based System Engineering*” – MBSE concept [19]. However, 2015 onwards simulation started playing an important role for essential activities of systems through the continuous support beside the entire cycle, for example, assisting function and service through the immediate and direct connection to the operational data. Offering simulation

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to the ensuing life-cycle stages corresponding to the system functionality and core product, for instance, strengthening the operation by simulation driven assistance, is the next big trend in simulation. The fine tuning of simulation software to yield an optimized performance is the one of the key challenges in DT. This fine calibration of simulation software help DT to simulate the activities much faster than the happenings in actual world. Subsequently, the DT can not only be used during system design but also during run time to predict system behavior online [8]. Details on the concept of DT, its definitions and history are the beyond the scope of this article. Readers may refer [16] for it.

In fact, the DT was invented and adopted in the aerospace domain of research and development. Recently, the manufacturing field has embraced the DT concept. However, the literature depicts that the concept of DT in the manufacturing is at the very early stage. In this direction, Cyber Physical System (CPS) opened the routes to an additional use, out of prognostics and diagnostics objectives. CPS has setup the meaning of DT for the production engineering domain. Many windows have been unlocked such as improved support to health analyses in order to enhance the planning and maintenance functions [9,23,10,17,5,21,6,7,12], creating a digital mirror of physical resources [15,19,3], Schluse and Rossmann [20,1,11], improved decision making capabilities for various statistical and engineering analyses [18,8,13,4]. In addition, the DT in its original sense appears as a tool to help in predicting of failures of system during lifecycle on the basis of data received from ground level through the sensors in the aerospace engineering domain [9,5,21], Kraft [13]. One of the very important and first understanding of DT is the underground relation to simulation tools that can be noticed in two ways viz., (i) DT is model to present the system based upon the various kinds of simulations techniques and tools [23,10,17,19,5,20,21,4,11] and, (ii) DT as the simulation of the system itself [9,15,8,13]. Even though, the simulation is in close connection and an important aspect associated with DT fundamentals, there are many authors who do not mention it [18,3,1]. Notwithstanding, of close relation among DT and simulation concepts, many researchers highlight distinct uses and physical characteristics. Thus, it is important to explore the simulation aspects in DT for better understanding of their relationship from proposed frameworks and direction of research viewpoint. In this direction, a review of the contributions on simulation-based DT and DT-based simulation has been presented for aerospace, manufacturing, and robotics applications. A review of the contributions on this would be highly beneficial, to pave the way and clarify the conceptual foundations for future research works on the adaptation of simulation techniques and simulation software to develop DT for various applications. Subsequent sections of this article discuss the simulation and DT in aerospace, manufacturing, and robotics. At the end, conclusions are drawn.

## 2. Simulation and DT in aerospace

In the aerospace, simulations replicate the continuous time history of flights, producing vast amount of data of simulations in order to recognize what the aircraft has undergone and to project forthcoming maintenance requirements and intrusions using various applications based simulation techniques, Computational Fluid Dynamics (CFD), Computer-Aided Engineering (CAE), Finite Element Methods (FEM) and Monte Carlo simulation [9,23,10,17,5,4]. A very few researchers underline that the simulation have to relate with the on-board sensors and devices to setup a constant harmonization along the ground situations [17].

From the aerospace viewpoint, DT can be defined as an integrating tool for a very-high-level realistic simulation setup with an on-board health platform of vehicle having all type of past data (such as maintenance and fleet) in order to accurately reflect the whole life as a flying twin which helps to facilitate the excellent trust and safely levels. DT is highly accurate and practical which can be independently as well as dependently considered for any system and subsystem of vehicle such as airframe, life support, energy storage and propulsion, thermal protection, avionics and many more. In addition, the DT encourage to integrate the material processing techniques with design of materials since the manufacturing glitches may seriously affect the vehicle [16]. Glaessgen and Stargel [9] proposed DT-based simulation for monitoring the manufacturing anomalies for health management and maintenance history for aeronautics and space applications. Reifsnider and Majumdar [17] presented a digital mirror (DT) of life of flying physical twin to predict the microcracks at early stage using integrated simulation and on-board health management system. They have discussed a response integral method and dielectric compliance as a foundation for stimulated simulation.

"*Structural Health Monitoring*" – SHM system is used to assess and analyze in-situ data of up-to-date capability of structural elements in order to make its planned functionality successful. In this direction, Bazilevs et al. [5] adopted "*Dynamic Data Driven Application System*" called DDDAS in which computational model of system was updated dynamically. They proposed FEM simulation-based DT for fatigue-damage prediction. They combined the models of fatigue-damage i.e. "*Iso-Geometric Analysis*" – IGA of thin-shell structures with the SHM to build up computational handling architecture. This combination was helpful to predict fatigue-damage in a full-scale laminated composite structure. They considered a fatigue test of wind-turbine blade and concluded the prediction of damage zone formation and evolution, eventually leading to blade failure. IGA is a FEM based simulation based on, animations, computer graphics and geometry of Computer Aided Design (CAD) model. IGA possess high order of continuity as compare to a regular FEM technique which is helpful in computational mechanics. DDDAS needs few active simulations to trial the stress conditions in structure for development of fatigue-damage status.

The mechanical structure of an aircraft is known as airframe. Airframe Digital Twin (ADT) is a tail number (i.e. aircraft registration number). In fact, ADT is computation model of an aircraft. It includes sub-models of electronics, propulsion systems, flight controls etc. ADT possessed a high degree of integration among sub-models in term of level of fidelity and computing uncertainties as compare to the conventional structural modeling techniques. Tuegel [23] developed virtual health sensor-based DT using FEM and Montecarlo simulations with the help of Damage and Durability Simulator (DDSim) simulation software to forecast the maintenance needs. They have proposed ADT to decrease maintenance cost by decreasing uncertainty and increasing service information using Bayesian updating method.

Gockel et al. [10] proposed a strategy called "*Condition Based Maintenance Plus Structural Integrity*" (CBM + SI) to generate high-level fidelity airframe stresses for an aircraft by capturing the complete flight data using a recorder. This data was used to fly a CFD model in order to find time history of aerodynamics load and then applying this time history to ADT. FEM based ABAQUS software was used to analysis temperature, stresses and strains. Ten points as well as flight routes were used for CFD simulation using Rocstar Simulation Suite. Authors concluded that only ten points in the sky were simulated independently, with linear-elastic response and only 0.1 s of flow simulated in CFD. A ready-made commercial software on a normal PC machine was used for structural response analysis in order to exploit parallel processing.

Integrating System Models and MBSE helps to set up the coordination among various disciplines such as mechanical, electrical, verification, software as well as other aspects of models and architectures throughout the lifecycle of any system. This approach can be termed as Total System Model (TSM) with a digital outline (DT). In fact, this combination has gained a lot of attention from researchers and practitioners since it involves several vendor tools as well as structurally regulated repositories process. In this direction, Bajaj et al. [4] proposed the integration of system engineering and mechanical design in which the CAE simulation-based DT was developed using Mathematica and MATLAB©/Simulink. The proposed TSM combine the system architecture model (SysML) with CAD, CAE, PLM, Application Lifecycle Management (ALM), Simulations methods, Project Management etc. They proposed Syndeia MBSE software platform (of InterCAX©) for seamless communication among systems engineering and various disciplines.

Smarslok et al. [22] proposed numerical simulation-based DT models for damage and life prediction including failure to make decisions in condition-based maintenance. They have integrated a variety of uncertainties in a connected hypersonic structural simulation. Wang et al. [25] proposed FEM and Montecarlo simulation-based DT for diagnostics and prognostics of aircrafts. They applied a fatigue mechanics and Extended Kalman Particle Filters (EKF) for layout optimization and Human-Machine Interface (HMI) interaction simulation.

Ríos et al [18] proposed Dassault Systemès (DS) V6 simulation-based DT for aircraft mockup to support design. They presented a collaborative model for the creation of an aircraft named "industrial Digital Mock-Up" iDMU, verified by a functional model and an iDMU dataset structure. DS V6 solution comprises several applications namely DELMIA© manufacturing hub, DELMIA© process engineering (DPE), DELMIA© digital process for manufacturing (DPM) and DELMIA© work instructions planning (WKI); and combines a manufacturing database with individual files. DS V6 framework provides a common database to store and retrieve industrialization data, facilitating the adoption of the parent product avatar proposed by Hribernik et al. (2006).

Simulation based prognosis of structural composites need a deep knowledge and understanding of mathematics for the process of interactions, material phase change over phenomenon owing to mechanical loadings and unloading. Majumdar et al. [15] proposed DT based simulation to investigate long term behavior of structural composites and their synergistic response under multiple environmental conditions. They studied the effects on structural performance in multi-physical environment (electrical field) which produce microstructural changes in structural composites. They conclude that increasing magnitude of electrical current can cause significant degradation. On the other hand, multi-physical behavior depends on local microstructure and resulting anisotropic nature of composite material.

Cerrone et al. [6] proposed a production-level simulation-based DT to monitor crack paths by filling information gaps which helps to predict crack path. FEM models of as-manufactured specimens are generated and subsequently analyzed to resolve the crack-path ambiguity. DT specimens are modeled and simulated in FEM based Abaqus/Explicit software package, to resolve crack path ambiguity in the "*Sandia Fracture Challenge*" – SFC geometry.

## 3. Simulation and DT in manufacturing

In manufacturing, the main objectives of simulation are to represent the complex behavior of the system, also considering the possible consequences of external factors, human interactions and design constraints [19,8,2]. Rosen et al. [19] proposed simulation-based DT for complex behavior of production in product life cycle. The proposed framework combining the real-life data with the simulation models from design to give predictions based on the realistic data. Kraft [13] proposed manned flight simulators DT for engineering analyses and decision making to forecast the crack propagation. Gabor et al. [8] proposed DT based simulation to optimize system behaviors during design phase in a smart CPS. Arisoy et al. [2] proposed HMI simulation-based DT for layout optimization. They introduced a data-driven approach for estimating natural grasp point locations on objects that human interact with in industrial applications. Schroder et al. (2016) proposed data exchange simulation-based DT to monitor physical entity.

The development of DTs for manufacturing is the next step for continuing research on Virtual Factories (VF). In fact, this is beyond the digitization of plant. The shop floor resources and activities are to integrate with the digital models by updating and simulating the complete production functionality while production for whole lifecycle of products and processes [14]. In general, the data and information gathered during the design stage of is not utilized at the operating stage. Although, the information of design is highly important for production stage in order to help in decision making process at the floor level as well as to easy the performance assessment. The research on VF need a structured and suitable semantic data model. In this direction, the semantic "*Virtual Factory Data Model*" – VFDM has been developed by [24]. They proposed a holistic way of production system based on consistent and stretchable criterion for collective description of various entities like processes, resources, buildings, and products of the factory.

## 4. Simulation and DT in robotics

In robotics, the simulation is mainly concern with the virtual commissioning of task in order to improve the control algorithms for robots in the course of development stage [20,11]. Simulation is the most effective source of information for robotics to prepare strategic plans, forecast, scale and measurements as well as to test various setting environments for different disciplines to improve the performance with respect to the cost and time. In general, the approaches for robot simulation is based on kinematic body dynamics. Many good simulation software's are available for commercial purpose. However, the most useful and well-known robot simulation software's are; (*i*) GAZEBO© and V-REP© focused on sensors and image based assemble systems, (*ii*) ROBOTRAN© a physics-based symbolic software to model and analyze multi-body systems, and (*iii*) ROBCAD© from SIMSOL working in association with SIEMENS©. These simulation tools are much effective and adaptable for planning and optimizing assembly system, robot factory and sensors.

Virtual Testbeds (VT) and DT (*eRobotics*) directs towards an "*experimentable DT*" which is a simulation-based development-and-operation of an intricated system. The testbed-based approach is very helpful to improve the traditional simulation methods. VT facilitate the assessment of full technical system in its nature. However, a normal simulation technique analyzes only few features and characteristics of an application. So, the VTs are well fitted to embody the DTs. For robotics, there is a need of an individual and all-inclusive as well as integrated 3D simulation architecture in order to apply all methods. In this direction, Schluse and Rossmann [20] presented MATLAB©/Simulink simulation-based DT for virtual commissioning having simulation at system level during design. The authors shown applications for on-orbit servicing, localization of forest machines, driver assistance systems and an industrial automation. They stated that the proposed approach is capable to integrate virtually any type of simulation. They have illustrated the micro kernel called "*Versatile Simulation Database*" – VSD which is object-oriented real-time database having a narrative of basic simulation model.

Mating of components is a major production step in automated assembly lines. Many aspects in mating two parts can be reduced to a peg-in-hole problem. When the parts are fitted to each other, jamming may occur, leading to assembly failure or damage to the parts, to the robot, or to its environment. Therefore, an intrinsically safe environment is required for the development and testing of new algorithms. Grinshpun, et al. [11] proposed "*Virtual Environment and Robotic Simulation*" – VEROSIM based DT to apply and optimize the algorithm for control of robots for virtual commissioning. They presented a workflow for developing control algorithms by means of a VT. Initially, they have created a virtual setup to test and optimize the algorithm in simulation. This setup comprises a DT of the used physical manipulator and an application-oriented virtual environment for its operation. Then an algorithm for peg-in-hole insertion is developed that copes successfully with peg and hole fitted to each other with small clearances. This algorithm is tested and validated using the DT within simulation. After its successfully validation in a VT, the algorithm is transferred to a physical setup containing the physical KUKA LWR4 manipulator and manufactured assembly parts.

## 5. Conclusions

It can be concluded that the simulation and DT technologies can execute virtual simulations models, but they are not same. A simulation in CAD/CAM/CAE are useful for product design, manufacturing, and analysis. DT have much more to do as compare to the traditional simulation. A virtual simulation model becomes a DT once the product is ready to use. For instance, (*i*) CAD simulation is static till a designer introduces a new parameter. While a DT begins its life as a model, it becomes more powerful when it starts to receive real-time data from its real-world counterpart. (*ii*) A CAD-based simulation replicates what could happen to the simulated product in the real world if specific changes are made to the design. While an IoT-powered DT learns from what is currently happening to its real-world counterpart, which allows the designer to see if the product is being used as intended and to make improvements based on the actual usage. (*iii*) A CAD-based simulation tends to be the purview of product designers and engineers, allowing them to test if/then scenarios as they change the simulation's parameters while designing a product. With DT, data from all stages of a product's lifecycle is fed back into each step. That means professionals can leverage a digital twin in as many parts of the business workflow as it simulates, providing access to the information they need to improve their processes and make business decisions.

Literature review clearly reveals that in aerospace industry, the simulation in DT replicate the continuous time history of flights, producing vast amount of data of simulations in order to recognize what the aircraft has undergone and to project forthcoming maintenance requirements and intrusions using various applications based simulation techniques, CFD, CAE, FEM and Monte Carlo simulation. A very few researchers underline that the simulation must relate with the on-board sensors and devices to setup a constant harmonization along the ground situations.

In manufacturing, the main objective of simulation in DT is to represent the complex behavior of the system, also considering the possible consequences of external factors, human interactions, and design constraints. The literature reveals that the concept of virtual factory is promising, and simulation-based DT is the added advantage to move beyond the digitization of plants.

In robotics, the simulation in DT is mainly concern with the virtual commissioning of task in order to improve the control algorithms for robots in the course of development stage using GAZEBO©, V-REP©, ROBOTRAN© and ROBCAD© simulation software.

It can be easily concluded that it is still to be explored on the integration of simulation and DT in the development process as well as in the overall life cycle of a system. Since the DT have to accurately simulate every part of system hardware. It may only be decided after testing multiple prototypes we are left with a typical chicken-and-egg problem.

It is worth to mention that the cost of computational power is still decreasing with technological advancements in hardware. In contrast, a simulation model with a refined encoding which can easily configure with the real environment is allow us to test the simulation of real observations and thus improve the performance of actual system. In addition, it should allow to integrate multiple real models and compatible with any version of a DT which may be plugged into the system.

## CRediT authorship contribution statement

**Rakesh Kumar Phanden:** Conceptualization, Writing - review & editing, Supervision. **Priavrat Sharma:** Writing - original draft, Formal analysis, Project administration. **Anubhav Dubey:** Writing - original draft, Formal analysis, Project administration.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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