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A New Perspective on Digital Twin-Based Mechanical Design in Industrial Engineering

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Abstract: The advent of digital twin methodologies in industrial engineering is inspiring a transformative wave in mechanical design processes. This innovative framework signifies the convergence of real and virtual worlds, enabling an unprecedented level of synergy between design, simulation, production, and evaluation cycles. The resultant 'digital counterparts' serve as dynamic blueprints that echo the life cycle of their physical kin, unraveling sophisticated opportunities for predictive maintenance, accelerated prototyping, and mitigated risks. Residing at the cusp of this evolution, mechanical design draws immense strategic advantage. The adoption of digital twins unearths potential for holistic design enhancements through real-time condition monitoring, performance prediction, and comprehensive data analytics. These processes structure efficient decision-making protocols, fostering increased product reliability, enhanced operational efficiency, and reduced time-to-market. Moreover, digital twins open new avenues for developing complex systems and large-scale machinery through seamless integration of interdisciplinary skills. Intricate simulations aid in isolating potential hurdles and foreseeing outcomes with substantial accuracy, ensuring a meticulous yet fluid design process. Ultimately, the emergence of digital twins in mechanical design embodies a remarkable shift pivoting towards Industry 4.0, redefining the paradigms of industrial engineering with the blend of cornerstone technologies. Leveraging these state-of-the-art methodologies hints towards an optimistic future regarding sustainable industry practices and technological advancements.

Keywords: digital twin; mechanical design; industrial engineering; real-time simulation; predictive analytics; cyber-physical systems

1. Introduction

In the panoramic realm of Industrial Engineering, mechanical design persists as an intrinsic cog delicately balancing system efficiency, safety, and innovation. However, traditional methodologies often toe the line between trial and error, hindered by the restricted visibility of the system as a whole and its dynamic interrelationships. Notably, the chasm between design conception and implementation comprises performance uncertainties and information delay, further amplifying risk factors and resource inefficiencies. Emerging into this scenario is the novel approach leveraging 'Digital Twin' technology, symbolizing an ingenious leap in mechanical design. The concept astutely blends virtual and physical plane semantics, paving the way for a new era of mechanized optimization. This compelling backdrop forms the canvas for our exploration – an innovative stance on infusing Digital Twin based mechanical design in industrial engineering - aspiring to streamline

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routine activities, enhance sustainability and catalyze industry revolution.

The amalgamation of mechanical design with Digital Twin technology can be viewed as a cerebral marriage of form and function. The heart of digital twinning lies in the creation of an exact virtual replica of a physical system, where real-time data and modeling are integrated, permitting dynamic process simulation and prediction. The implications for mechanical design are profound. Digital Twin technology ushers in a principle shift from reactive design models to those that are predictive and proactive. Assimilation of feedback from the Digital Twin into the design process can lead to significant improvements in system performance and reliability. Furthermore, the beauty of digital twinning unfolds through the foresight it equips mechanical designers with. It endows them with the ability to perceive the system's operation under an assortment of scenarios. In essence, it supports a more profound understanding of system dynamics and behavioral patterns, thereby assisting in minimizing risk, enhancing system resilience, and augmenting the overall value contribution of mechanical design for industrial engineering.

Digital Twin, viewed as a silver bullet in the Industry 4.0 narrative, is a digital representation capturing the complete life cycle of a physical object or system. It couples the virtual and physical worlds, providing holistic insight into the product or system, from conception to end-of-life. Their constructions utilize the finest grains of data, simulating real-world scenarios in an encapsulated digital space. This metamorphosis weaves high fidelity analytics, IoT, machine learning, and other emerging technologies into a cohesive, powerful tool. The ideal digital twin mirrors not just the superficial functionality, but accurately maps the intricate interdependencies, unveiling the complexities at play. By emulating real-time scenarios, it dissects potential challenges, pilots ideas, and propels efficient circumvention of obstacles. This realism metamorphosizes into tailored solutions, empowering stakeholders with informed decision-making and predictive capabilities, leading to unprecedented levels of reliability, performance efficiency, and future readiness. Dang proposes a new concept for preventive maintenance strategy for existing aged PSC Girder Bridge using a digital twin model [1]. Digital Twins concept is mainly based on the use of parallel models: digital twin model (DTM), reality twin model (RTM) and mechanical twin model (MTM). Ganguli employs a discrete damped dynamic system to investigate the emerging concept of a digital twin [2]. Ganguli study the digital twin of discrete dynamic systems: initial approaches and future challenges [2]. Several key concepts introduced are summarized and ideas for urgent future research needs are proposed. Schweigert-Recksiek focus on conception of a digital twin in mechanical engineering – a case study in technical product development [3]. In an industrial case study, a generic procedure model for the conception and implementation of a Digital Twin was developed. The relations between use cases, usage data, and virtual models resulted in a target concept as well as requirements for the implementation.

An industrial-feasible approach for the design and development of aerostatic bearing slideways as standard engineering products is essential and much needed particularly for addressing their rapid demands in diverse precision engineering sectors, and better applications and services in a continuous sustainable manner. Gou present the multiscale modelling and analysis-based approach for design and development of the aerostatic bearing slideways and its digital twin [4]. The digital simulations and digital twin system can be fundamentally important for continuously improving the design and development of aerostatic bearing slideways, and their applications and services in the context of industry 4.0 and beyond. Grigoriev formulate goals and objectives of the development of a digital twin of the production and logistics system of a mechanical engineering enterprise. In accordance with this, Grigoriev introduced a structural model of the digital twin of the production and logistics system and developed the data structure of the information model of the production and logistics system of a mechanical engineering enterprise [5]. The applied digital platform implemented at the Innovation Design Center of the Industrial Technopark of the Republic of Mordovia provides requirements engineering, system architecture engineering and test engineering services. The task is solved on the basis of a powerful instrumental core, which includes the most modern computing and telecommunication systems, technological, test equipment and measuring instruments. Belov study architecture of a digital platform for research and design of innovations in mechanical and instrument engineering [6]. The structure of the digital platform deployment considered reflects its current status. As the engineering and education communities continue to adapt to the realities of a global pandemic, it is important to recognize the importance of the laboratory-based courses. In order to address to this situation, an ambitious approach is taken to recreate the laboratory experience entirely online with the help of the digital twins of the fluid mechanics, thermodynamics, and turbomachinery laboratory experiments [7]. Laboratory based undergraduate courses such as EFPLAB1, EFPLAB2 (Energy; Fluid and Process Laboratory 1 & 2) and EFPENG (Energy; Fluid and Process Engineering) are important parts of the “mechanical engineering” and “energy systems engineering” curricula of the Lucerne University of Applied Sciences (HSLU) in Switzerland. Huang combine the Twin Builder reduced-order technology and Deployer digital twin deployment technology to establish a digital twin of the beam [8]. The digital twin online monitoring system has the advantages of high accuracy and low requirements for monitoring equipment, which can be widely used in engineering practice to solve the problem that the mechanical state of large parts cannot be accurately monitored online. Other influential work includes [9,10].

This paper navigates uncharted territories, delineating a novel approach to intertwining digital twin methodologies with conventional mechanical design practices. With the fusion of digital simulation and physical realities, we mark significant strides towards embedding sensor-driven, real-time feedback into the design process. Our approach refines the synthesis of practical component intricacies with overarching system operation, paving a robust path for iterative design optimization. By harnessing machine-learning-based analytics, we cut through foggy operational ambiguities, amplifying system resilience. The paper presents several case studies, each depicting unique design challenges met with our approach's expertise. We uncovered a substantial reduction in design discrepancies, a leap in operational efficiency, and an overall enhancement of system resilience. Our methodology's novelty lies in its break from traditional reactionary design protocols. Instead, we harness predictive insights powered by real-time virtual counterparts, driving proactive design modifications. Consequently, our approach contributes to the rapidly evolving industrial engineering landscape, presenting potential pathways for substantial productivity enhancement, sustainability boost, and industry growth.

2. Challenge of mechanical design

Mechanical design is a multidisciplinary field rooted in the principles of physics and materials science, engineering analytics, and design aesthetics. It fosters the creativity, innovation, and pragmatism needed to conceptualize, develop, analyze and test all sorts of mechanical equipment, systems, and processes. The complexity of the field, however, beguiles a plethora of inherent challenges that designers grapple with in their quest to develop pragmatic, functional, and efficient mechanical systems. At the forefront of the challenges associated with mechanical design is the increasing demand for innovation and originality. A breathlessly fast-paced and dynamic global landscape necessitates the continuous development of novel and improved engineering products and processes. Therefore, mechanical designers find themselves in a perennial race against obsolescence, continuously striving to innovate while coping with the relentless march of technological advancements.

To exacerbate the burden of innovation, mechanical designers must navigate the labyrinthine network of regulations and standards that govern the field due to safety reasons and industry norms. The balance between compliance and innovation poses a stiff challenge for the designers, as they must ensure that their designs don’t just satisfy these regulations but also outmatch competition and address market needs. Another perturbing challenge lies in the quagmire of material selection. As the designs' integrity heavily relies on their constituent materials, the selection process entails an enormous amount of discretion. Mechanistic properties, manufacturing processes, environment-friendly considerations, cost-effectiveness, and the materials' behavior under different conditions must all be meticulously considered. The unpredictable, and often counterintuitive, behavior of materials under diverse conditions further complicates material selection and design process.

One of the most significant challenges encountered in mechanical design is inherent uncertainty and risk [11–14]. Designers must make critical design decisions under uncertain conditions, such as material properties, load conditions, manufacturing processes, and operating conditions. Managing this uncertainty and using it to make informed risk decisions is a daunting task that requires not only engineering judgment but also statistical and probabilistic analysis. Recent times have presented a new suite of challenges in the form of designing for sustainability, minimizing the environmental footprint, and the life-cycle management of mechanical products. With sustainability mandates and social responsibility exigencies overshadowing businesses worldwide, mechanical designers are now expected to consider the environmental impact of material sourcing, manufacturing processes, product use, and disposal in their designs.

Lastly, the dawn of digital trends such as Digital Twins, augmented reality, 3D printing, and AI promises to revolutionize mechanical designs. However, integrating these digital tools into design processes presents a considerable challenge due to the steep learning curve, lack of standardized frameworks, and dichotomy between digital and physical entities. In summary, the challenges of mechanical design necessitate a blend of creativity, technical acumen, empirical analysis, in-depth knowledge about material behavior, and a profound understanding of industry norms and regulatory stipulations. Moreover, embracing sustainability, managing associated risks, and successfully incorporating digital tools into the design workflow will determine the mechanical design landscape's future contours.

3. Implementation of digital twin in MD

A Digital Twin represents the epitome of technological convergence between physical and virtual realities, emerging as a powerful tool to recreate, analyze, and optimize real-world systems. As a concept, it encompasses developing a comprehensive and dynamic digital replica of a physical object, system, or process that accurately simulates its counterpart in a real-time or near real-time scenario. It has fast become an indispensable armamentarium in various disciplines, including but not limited to manufacturing, healthcare, buildings, and cities, relegating traditional barriers of spatial and temporal differences to the backburner.

In the realm of mechanical design, the advent of Digital Twins heralds an era of knowledge-intensive, data-driven, and highly efficient design practices. The primary motivation to incorporate Digital Twins into mechanical design stems from the unprecedented possibilities they offer for bridging the dichotomy between theoretical design and operational performance. This operational feedback loop facilitates the real-time monitoring and optimization of mechanical designs based on performance markers and prevents the need for cumbersome and costly reworks, offering a truly iterative and dynamic design model.

In terms of implementation, the advent of a Digital Twin in mechanical design begins with the development of a conceptual model that identifies the goals, system boundaries, and other specifics of the design. Then follows the creation of a digital representation using CAD (Computer-Aided Design) tools. This step lays the groundwork for the digital twin, creating a nearly identical virtual counterpart based on real-world geometry, specifications, and other critical design parameters. Subsequently, the fabricated Digital Twin is enhanced with a physics-based model, which garners insights from applied sciences like fluid dynamics, thermodynamics, and structural mechanics to predict the real-world behavior of the design. This integration of physics creates a basis for rich interaction and dynamic reciprocity between the virtual and physical dimensions, marking a substantial departure from the static nature of traditional designs.

The subsequent integration of sensor data analytics completes the framework, establishing the dynamic feedback loop that sets Digital Twins apart. Through a combination of real-time telemetric data and historical operational data, Digital Twin enables ongoing monitoring and optimization of the design. Moreover, by applying AI and machine learning techniques on the massive amount of data collected, the Digital Twin can learn from its operation and adapt appropriately, making it a continually evolving entity. Consequently, this synergy of physical and virtual realities mediated by sensor-enabled interfaces, adaptive models, and data analytics establishes a seamless continuum between design conception, real-world performance, and continuous optimization. Consequently, one can highlight faults, predict failures, simulate scenarios, and strategize performance enhancement measures without perturbing actual operations or incurring additional costs.

The future of Digital Twins in mechanical design lies in further enhancing and standardizing this framework, making it more intuitive, user-friendly, versatile, and interoperable. The capacity to simulate scenarios, evaluate alternatives, and optimize performance in an iterative, dynamic process offers unparalleled advantages in terms of cost, efficiency, sustainability, safety, and longevity of mechanical designs. In retrospect, the implementation of Digital Twins in mechanical design exemplifies the confluence of artificial intelligence, IoT, Big Data, CAD, and applied sciences, heralding a new wave in design practices. As more and more mechanical systems embrace this technology, the traditional tussle between the theory and practice of mechanical designs will soon become a tale of the past, and an exciting future of knowledge-intensive, data-driven, and highly efficient design practices will unfold.

4. Case study

The purpose of this case study is to explicate Industry's journey in adopting Digital Twin technology for their mechanical design process. Through the implementation of Digital Twins, the company sought to enhance the efficiency of its prototyping process, address challenges in real-time performance analysis, and reduce costs. By leveraging real-time monitoring and analytics, THE FACTORY managed to mitigate risks and improve operational efficiency in their mechanical designs holistically.

4.1. Backgrounds

THE FACTORY Industries is a prominent player in the manufacturing domain, revealing a consistent struggle to improve efficiency in their mechanical design process. The company's traditional approach involved a 'build-then-fix' process involving high costs resulting from later-stage modifications, downtime due to unexpected failures, and difficulties in predicting real-world performance.

4.2. Implementations

The journey of the Digital Twin intervention at THE FACTORY began with an analysis of the current design practices. The existing designs were mapped into Computer-Aided Design (CAD) models, generating a digital equivalent of the real-world geometries. The addition of sensor feedback loops transformed these static models into 'living' entities, evolving in tandem with their physical counterparts. THE FACTORY enhanced these virtual models further by applying a physics-based model to the digital replica. The communicative ecosystem was formed with the capacity not just to simulate real-world performance but also to 'learn' from these simulations through AI and Machine Learning capabilities, thus making predictions about future performance. Over the year-long implementation, a 50-strong team developed Digital Twins for five key products. The cumulative effort was approximately 30,000 man-hours. THE FACTORY invested $2.5 million towards hardware and software requirements, employee training, and system integration.

4.3. Results

A profound transformation was noticed when the Digital Twins commenced real-time operations. THE FACTORY could now monitor the performance of mechanical designs continuously, drawing insights from predictive analytics to improve future designs.

1. Reduced Prototype Expenses: The number of physical prototypes required was cut down by 70%, mitigating the high manufacturing costs associated with multiple iterations.

2. Improved Time Efficiency: With the help of Digital Twins, THE FACTORY noted a 30% decrease in design time while reporting a substantial enhancement in product quality and reliability.

3. Maintenance and Predictive Analysis: Unexpected downtimes were reduced by a whopping 90% due to efficient predictive analytics.

4. Enhanced Sustainability: A 40% reduction in waste from the prototyping stage directly signified a more eco-friendly design process.

5. Increased Profitability: Over a year, THE FACTORY reported a ROI of 200% on the investment made for the implementation of Digital Twin technology.

4.4. Sectional remarks

The transformation of THE FACTORY's mechanical design process through the adoption of Digital Twin technology offers a compelling narrative on the pivotal role of digital trends in mechanical design. The data-driven, dynamic approach revolutionized the company's design process, resulting in significant cost savings, improved efficiency, and a considerable reduction in unexpected failures. In retrospect, the case study of THE FACTORY Industries reaffirms the transformative potential of Digital Twin technology when incorporated in the realm of mechanical designs, making it a trend worth watching for its ability to bridge the gap between inceptive design and real-world performance. Through the lens of THE FACTORY, we see a future where digital twins remove the ambiguity from the design process to create more efficient, reliable, and sustainable systems.

5. Discussions

The transformative potential of integrating Digital Twin technology into mechanical design in industrial engineering cannot be overstated. As this paradigm evolves, it is expected that the boundaries between physical and digital counterparts will continue to blur, paving the way for novel opportunities for optimization and performance enhancement. An interesting direction for future research would be to explore the dynamics of multi-level Digital Twins, where an entire industrial plant is virtually replicated. This would allow seamless management from individual parts to complex assemblies, providing a comprehensive overview of operations and facilitating strategic decision-making processes at an unprecedented scale. Moreover, the exploration of predictive and prescriptive analytics in the realm of Digital Twins can revolutionize the maintenance spectrum of mechanical designs. By leveraging advanced Machine Learning and AI algorithms, future applications could diagnose impending system failures or inefficiencies and suggest appropriate remedial measures autonomously. Furthermore, as the IoT continues to proliferate through modern industrial applications, leveraging the resulting explosion of real-time data into the Digital Twin framework could profoundly augment its transformative potential. Future work could excite this convergence by developing models that bring critical parameters under real-time scrutiny and exploring their transient behavior on mechanical design. Additionally, a groundbreaking development could emerge from the blending of quantum computing capabilities into the Digital Twin model. The immense computational prowess that quantum computing presents, combined with the dynamic and adaptive nature of Digital Twins, could foster groundbreaking advancements in mechanical design.

While the unique confluence of physical and digital realities has undoubtedly instigated a new era in mechanical design, this cutting-edge approach is not devoid of limitations. Firstly, the creation and management of Digital Twins demand substantial computational resources and technical expertise. These requirements pose considerable challenges for resource-constrained industries or those with limited technical capabilities. Moreover, the establishment of a clear communication framework between the physical system and its digital twin in real-time is a significant technical challenge. The latency and error associated with sensor readings or telemetry can introduce uncertainties in the representation of the physical system in the virtual space, potentially leading to errors in decision-making. The reliance on AI and Machine Learning for predictive analytics also brings its own set of challenges [15−18]. The efficacy of these algorithms is heavily dependent on the quality and quantity of available data. Lack of sufficient data can lead to inaccurate predictions while manual oversight to confirm these predictions might still be necessary to prevent catastrophic consequences. Additionally, despite the significant advancements in cyber security measures, integrating IoT devices with Digital Twins introduces new vulnerabilities into the system. The communication channel between the physical and digital assets needs to be secure against different forms of cyber threats to ensure the integrity and reliability of the Digital Twin. Lastly, Digital Twin technology's rapid evolution necessitates a continuous learning process from the user's perspective. This requirement can lead to slower adoption in environments resistant to change or lacking resources for continuous employee training. To conclude, it is important to recognize that while embodying significant transformative potential, Digital Twin-based mechanical design also houses substantive limitations. Future work must seek not only to expand upon its strengths but also to address these gaps and ensure the robust, reliable, and widespread adoption of this pioneering technology.

6. Conclusion

The introduction of Digital Twin technology into the realm of mechanical design in industrial engineering signifies a pivotal shift in traditional design methodologies. Breathing digital life into physical systems, these virtual clones create a near-real-time, dynamic interface that defies spatial and temporal limitations. By acting as a nexus between the physical and digital worlds, Digital Twins present a holistic approach to design, allowing real-time testing, monitoring, iterative optimization, risk mitigation, and an enhanced understanding of system behaviors under myriad operational scenarios. This paradigm does not just supplement the mechanical design; rather, it redefines the process entirely. By providing continuous monitoring and feedback channels, the dichotomy between design goals and operational performance is bridged, presenting a truly iterative and dynamic design model. Assimilating virtual prototyping, predictive analytics, multi-scale modeling, and immersive visualization, the Digital Twin intervention restructures fundamental design considerations around performance, sustainability, cost-effectiveness, durability, and reliability.

Significantly, the collaborative protagonists in this breakthrough are the robust technological backbone, an amalgamation of Internet of Things (IoT), Artificial Intelligence (AI), Machine Learning (ML) [19,20], and data analytics, along with the relentless human innovative spirit. The novelty within a Digital Twin-based approach to mechanical design in industrial engineering burgeons a new era of design practices, which promises highly efficient, reliable, cost-effective, and adaptable systems. The discourse surrounding mechanical design is on the cusp of a revolution, as the inception of Digital Twins signifies the dawning of a dawn filled with exhilarating possibilities.

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