On Web Digital Twins: an use case for a Gerotor pump

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ABSTRACT

In the current wave of digital industry, Digital Twins play a major role in the virtualization of manufacturing processes. Digital Twins are virtual entities that mirror the behavior of physical entitites. They are used to predict or monitor the information of a product or a process. In recent years, virtualization technologies have benefited from cloud computing and web-based services to enhance the capabilities of industrial Digital Twins. These *Web Digital Twins* enable greater degree of distribution and collaboration between the users of the Digital Twin. In this article we present an use case of web-based Digital Twins for the design and monitoring of Gerotor pumps. The novelties of the present article are: i) it highlights the advantages that result from applying the Digital Twin methodology to the case of Gerotor pumps, ii) it describes the implementation of a web-based Digital Twin tool for a Gerotor pump. Our tool allows the user to design a Gerotor pump using a parametric interface, visualize the 3D model of the pump, visualize its expected performance using fast simulation routines and obtain the optimum design for a set of desired performance parameters. This article focuses on the technological overview of the Digital Twin tool and its web-based architecture, as the simulation and optimization details were addressed in different publications.

CCS CONCEPTS

• **Computer systems organization** → Real-time systems; • **Applied computing** → **Computer-aided design**; • **Computing methodologies** → **Rendering**.

KEYWORDS

web, industry 4.0, digital twins, gerotor pumps, simulation, visualization

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1 INTRODUCTION

In this section we make some introductory comments on three relevant notions that underlie our work: systems and their representations, the digital twin representation and its possibilities when used in combination with web-based technologies.

1.1 On systems and their representations

Any physical system can be characterized by the information it produces. Even the simplest systems, those consisting of a single element, can be thought of as an ordered disposition of information. For example, any machine as simple as a hammer is characterized by different information flows: its spatial information (a particular geometry, position, etc.), its physical information (mass, density, material, etc.) and its functional information (the amount of force it conveys, the amount of vibration, etc.). Two important aspects of this information-driven characterization of systems are: i) identification of relationships between information flows and ii) representation of both information flows and the relationships between information flows.

A system can be considered simple or complex according to the intricacy of the relationships between its information flows. For example, in a simple machine such as a hammer the relationship between its spatial information (shape) and functional information (force transmitted) is clear and well-known. Complex systems are those in which the relationships between the information flows of the system are not known at all or known with a lesser degree of certainty. Two interesting questions any observer could ask of a system are a) what is the current state of the system? and b) what will be the state of the system in a given future time? To answer the first question, it is enough to query the system for its current information flows using measurement devices such as sensors. The answer to the second question requires knowledge of the relationships between information flows and a way to represent them quantitatively. Complex systems, however, pose important constraints on the ability to answer these questions, as it usually requires time-, computing- or money-intensive procedures and tools. Virtual representations arise as a way to answer these two questions for complex systems in a more efficient way.

1.2 On Digital Twins

Digital Twin (DT) is a notion attributed to Michael Grieves [Grieves 2005] in the context of Product Lifecycle Management (PLM). Figure 1 shows an overview of the general architecture of a Digital Twin representation. Grieves describes the Digital Twin as *a set of virtual information constructs that fully describes the potential or actual physical manufactured product* [Grieves 2005]. Three words are key in this definition: *fully*, *potential* and *actual*. *Fully* means that a full Digital Twin should account for all the possible information flows of the system. *Potential* refers to the simulation capabilities a full Digital Twin should have and *actual* to the representation capabilities of the current state of the physical system.

To this day, a full Digital Twin has not yet been achieved, at least in the sense of Grieve's definition. Advances in CAD modeling, sensor technology, 3D visualization, mechanical simulation and other areas open the way to partial Digital Twins, that is, virtual architectures that represent *some* (but not all) information flows of a particular product. Other definitions of Digital Twins, such as the ones presented in [Glaessgen and Stargel 2012] and [Erkoyuncu et al. 2018] extend the definition to assemblies of physical items. Furthermore, Grieve's definition has been extended to include not only physical manufactured products but the production processes of these products. Given this fact, we consider a Digital Twin to be *any virtual entity that represents the information flows of a system and the relationships between these flows*. To this day, no unified definition of a Digital Twin has been achieved, as it is a notion used in very different fields each with different requirements.

1.3 On web services applied to Digital Twins

Cloud computing and web services add to the potential of a Digital Twin in the following aspects: i) they enable the notion of a *distributed* Digital Twin, that is, a virtual representation of a system that is geographically distributed in different locations; ii) web services facilitate the real-time link between the physical space and virtual space, specially when the objects in physical space are in movement; iii) from the user side, it allows several users to access the Digital Twin interface at the same time and from different locations.

The virtues of web services applied to Digital Twins become evident by the proliferation of technological frameworks oriented to the construction of these web-based Digital Twins. Some examples are Google's Supply Chain Twin, Amazon's IoT Twinmaker, Siemens' Xcelerator and Nvidia's Omniverse. In Section 2 we present an overview of the current state of web-based Digital Twin technology in the scientific literature. In Section 3 we present an use case of a web-based Digital Twin.

Our work presents an early and partial Digital Twin of a gerotor pump with monitoring, simulation and optimization capabilities. Section 4 concludes the article and delineates the next steps to achieve a full Digital Twin of a gerotor pump.

2 RELATED WORKS

In this section we present an overview of the current state of Digital Twin technology highlighting those applications that use web-based services. The Digital Twin name has been applied to many different entities that mirror the physical world up to a certain degree of resemblance. Digital Twins have been developed to mirror the human body [Barnabas and Raj 2020; Erol et al. 2020], cities [Deng et al. 2021; Shahat et al. 2021], natural ecosystems [Bauer et al. 2021; Blair 2021], but it is industry where the notion was born and is most used. Industrial Digital Twins are ubiquitous now in all fields of engineering technology. Production lines [Park et al. 2020; Vachálek et al. 2017], cutting machinery [Botkina et al. 2018; Luo et al. 2020], engine manufacturing [Bambura et al. 2020], aviation parts [Xiong and Wang 2022], amongst many other fields, have benefited from Digital Twin applications. For an extensive review of Digital Twins in industry we refer the reader to [Jiang et al. 2021].

Many recent research has focused on the use of web services and cloud computing to Digital Twin applications. For example, the IoTwins project [Costantini et al. 2022] proposes a highly distributed and hybrid digital twin model with a cloud-based data transfer streamline. Mateev [Mateev 2020] presents business cases for web-based IoT solutions for buildings powered by Digital Twins, along with a demo application using Microsoft Azure platform. Uhlenkamp et al. [Uhlenkamp et al. 2022] develop a maturity model used to evaluate a leisure boat Digital Twin with computational fluid dynamics (CFD) simulations on a high performance computing cloud. Ricci et al. [Ricci et al. 2022] present the concept of *Web of Digital Twins*, which can be summarized as a cloud-driven ecosystem of connected digital twins. This concept aims to mirror large-scale interrelated physical realities. Autiosalo et al. [Autiosalo et al. 2021] present a web-based prototype implementation of an industrial digital twin for an overhead crane. Their prototype uses web-based solutions for graphic interface, user identification and data gathering from sensors. A similar research was presented by Hietala et al. [Hietala et al. 2020] which develops a web-based application program interface (API) that simplifies transferring data for Digital Twin solutions. Lei et al. [Lei et al. 2021] present the use case of a web-based digital twin for a thermal power plant including real-time monitoring and visualization. Stan et al. [Stan et al. 2022] present a Digital Twin for a robotic deburring workcell. The presented solution uses a web platform to remotely monitor the robotic workcell.

The previous works testify to the importance of web-based Digital Twins in the current wave of industrial digitalization in a wide variety of fields. Hydraulic-related applications, pumps amongst them, are no exception to the use of Digital Twins, even though the current solutions mostly do not use a web-based approach and are very scarce. The review made by Yang et al. [Yang et al. 2022] concluded that very few applications of Digital Twin methodologies to hydraulic pumps exist, thus making the present article an attractive one. References [Bonilla et al. 2022] and [He et al. 2022] present Digital Twins of a water distribution system and a pumping station respectively. MacDonald et al. [MacDonald et al. 2017] present a Digital Twin of a pump that relies on a cloud-based CFD simulation model. Kosova et al. [Kosova and Unver 2023] present a Digital Twin framework for machine learning-driven detection

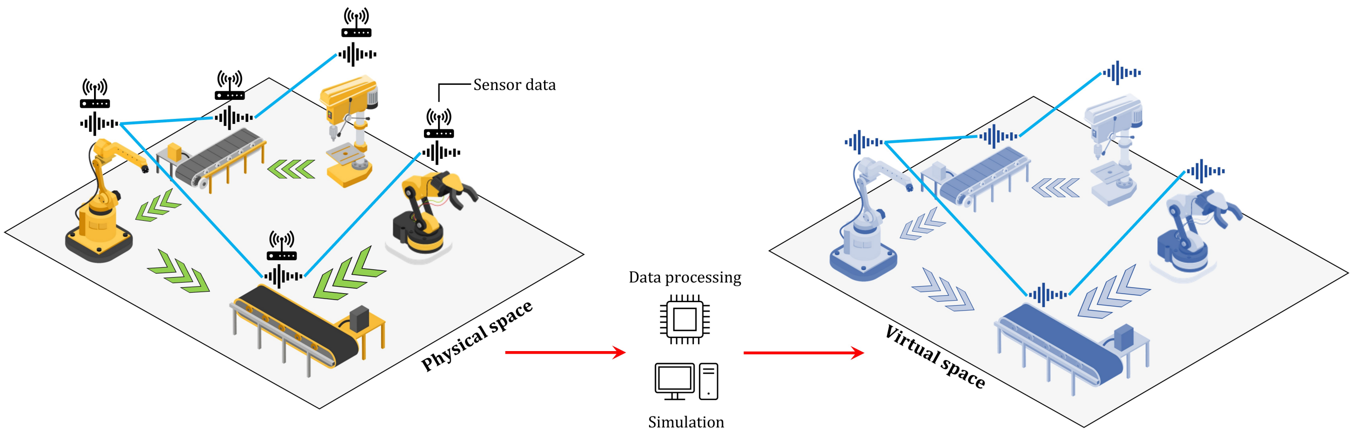

Figure 1: A Digital Twin's general architecture

of failures in aircraft hydraulic systems. Kasat et al. [Kasat et al. 2023] present a Digital Twin tool for performance evaluation of centrifugal pumps.

The few applications available of Digital Twins to hydraulic pumps are very recent, therefore highlighting the growing relevance of this particular topic. The existing approaches do not address the specific case of Gerotor pumps or the use of web technologies in the Digital Twin tools. In this article we present a web-based Digital Twin of a gerotor hydraulic pump that integrates a) geometrical design, b) light and fast performance simulation, c) geometric optimization of the pump's design.

3 WEB DIGITAL TWIN OF A GEROTOR PUMP

In this section we present a web-based tool that displays the virtues of using a Digital Twin architecture to develop a virtual model of a Gerotor pump. Our tool allows the user to a) design a Gerotor pump using a parametric design environment, b) visualize the'dynamic 2-dimensional and 3-dimensional model of the pump, c) visualize the expected performance of the pump calculated using fast and light simulation algorithms, d) load sensor and computational fluid dynamics (CFD) data to the Digital Twin to compare with the simulated performance, e) obtain the optimum profile for a desired output flowrate. First, we make a brief introduction to Gerotor pumps. Then we present the architecture of the Digital Twin tool and the implementation in a web-based environment. This section focuses on the technological overview of the Digital Twin tool. The scientific details of the fast simulation routines are addressed in a previous publication by the authors [Pareja-Corcho et al. 2021] and in an upcoming publication.

3.1 Gerotor Pumps

Gerotor pumps are internal gear volumetric pumps popular in manufacturing, automotive, medical and aerospace applications [Gamez-Montero et al. 2019]. In simple terms, volumetric pumps are devices that receive fluid at a certain conditions of pressure and speed and deliver them at a a different level of pressure and speed. They are usually used to accelerate fluid in a hydraulic system. Gerotor pumps are attractive because of their relative low cost with respect to other solutions, compactness and robustness. A Gerotor pump is composed of two gears: an external gear with n teeth and an internal gear (that rotates within the external gear in an epicyclic disposition) with $n-1$ teeth. This disposition creates a set of volume chambers between the gears in which the fluid enters. The relative movement between the gears causes the volume chambers to either reduce or increase in volume depending on the position of the chamber in the pump and effectively forcing the fluid inside the chamber to move outwards.

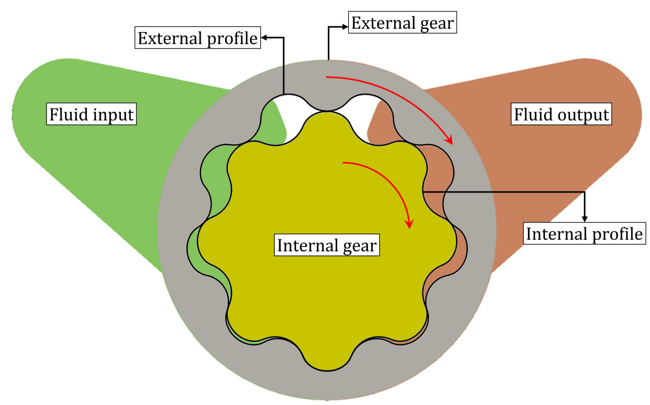

Figure 2: Scheme of a typical Gerotor pump

Figure 2 shows the geometric configuration and working of a Gerotor pump. Some of the aspects that affect the suitability of a particular pump for a given application are i) the profile of the gears, ii) the desired output flowrate, iii) the volumetric efficiency of the pump, iv) the mechanical efficiency of the pump. The profile of the gears refers to the meshing curves between the gears. These curves are usually trochoidal, for the case of Gerotor pumps. The output flowrate refers to the amount of fluid that the pump is able to deliver in a certain amount of time. The volumetric efficiency refers to the ratio between the actual flowrate of the pump and its theoretical flowrate. The mechanical efficiency refers to the ratio between the energy delivered to the fluid and the total energy received by the pump.

All these aspects should be accounted for in a Digital Twin of a Gerotor pump, at least in its initial stages, to account for the general characterization of the pump. Furthermore, this Digital Twin should have simulation capabilities to aid the users in the design stage and monitoring capabilities to track the performance of the pump in a physical test bench (and, eventually, in real time operation).

3.2 Why a Digital Twin?

One way to evaluate the pertinence and relevance of a Digital Twin to the lifecycle of a product is the Six M methodology [Hu et al. 2022]. This methodology postulates six dimensions to be considered when discussing the Digital Twin: Machine, Manpower, Material, Measurement, Milieu and Method. We will give some remarks on the case of Gerotor pumps for each dimension to highlight the advantages of a Digital Twin in this particular application.

3.2.1 Machine. This dimension refers to all physical assets and equipments. A DT of a Gerotor pump must visually represent the pump itself; that is, its constituent components and the dynamic relations between the components. This can be done with any desired degree of detail. In an early-stage DT such as ours, the represented components are limited to the inner and outer gears and to the input and output ports. The basic rotational movement of the gears is animated but more complex phenomena such as vibrations are left out. The visual representation of the physical pump aids to evaluate the manufacturing feasibility of a design and the correctness of its dynamic behaviour.

3.2.2 Measurement. This dimension refers to the quantifiable information produced by the virtual and physical asset (e.g. cost, price, efficiency, sizes). The main information one desires to obtain from a DT of a Gerotor pump is how good is the pump's design. This must be evaluated in several aspects: Does the pump produces the amount of flowrate required for my application? How efficient is the pump? Is it the correct size for my application? What are the pressure conditions needed to produce the target flowrate? What is the effect on the pump's performance if the design changes slightly? All these questions must be answered by the Digital Twin of the pump.

3.2.3 Manpower. This dimension refers to the working force engaged with the physical asset. The information produced by the Digital Twin must be assessed by the *design engineer* to determine if it fits the design requirements. For example, the DT can simulate the expected output flowrate for a particular design, but this quantity by itself says nothing about the suitability of such design. It is the engineer, with his knowledge of the application and environment in which the pump will operate, who will determine if the expected output flowrate satisfies the industrial requirements. With a Digital Twin tool, the engineer is provided with fast feedback on a particular design and can make faster and better informed choices.

3.2.4 Material. This dimension refers to the raw materials involved in the process. A fully capable Digital Twin should be able to account for both the pump's material and the fluid's characteristics. The pump's materials affect the performance of the pump specially due to the contact forces between the gears and the stresses they induce on the gears. The fluid's characteristics (e.g. density, air fraction, bulk modulus, temperature) also affects the performance of the pump. Our tool currently considers the density of the fluid but does not yet considers other characteristics such as air fraction (which is crucial to account for cavitation phenomena). The consideration of these factors allows the engineer to evaluate and predict how the same pump will perform for different fluids or temperature conditions.

3.2.5 Milieu. This dimension refers to the physical environment in which the asset carries out its function. In the case of Gerotor pumps, these usually operate as a part of a larger hydraulic system that dictate the operation conditions for the pump itself (e.g. the input and output pressures). If a Digital Twin includes the possible variations in the conditions of the larger hydraulic system in which the pump operates, it will provide the engineer with a wider range of responses from the pump, thus increasing the information available to him/her. This can be critical in evaluation of extreme operation conditions when the hydraulic system malfunctions and how will the pump respond to such conditions.

3.2.6 Method. This dimension refers to approaches used to improve the performance of the physical asset. The main approach to optimize the performance a pump is to find the optimal curve for the pump's profiles that satisfy a set of constraints (e.g. desired flowrate, operation pressures, etc.). The Digital Twin integrates both measured and simulated data from a range of operation conditions and geometric profiles. One of the benefits of building a Digital Twin is to use these data to predict optimal configurations of the pump for a particular set of operation conditions.

3.3 Architecture of the Web Digital Twin

The architecture of the Digital Twin tool (Figure 3) could be summarized in three main components: in the client side are executed the user interface (UI), the geometric calculations of a particular design and the light efficiency simulation routines; the server side handles the database management and runs the optimization routines when requested by the client; finally, the physical test bench is equipped with sensors to monitor the interest variables on the physical pump in operation.

The user interface hosts the following functionalities: a) interface for parametric design of the gerotor pump, b) 3D model visualization, c) data visualization from the simulation/optimization module, the geometric calculations and the physical test bench. The parametric design of the gerotor pump consists on generating the trochoidal curve of the internal gear according to a set of input parameters. The curve profile of the external gear is then calculated using an envelope curve method. Additionally, the history of volumes of the fluid chambers is calculated for a full revolution of the pump. After the geometric module builds the 2D shape of the pump, the CAD models of the designed gears are generated using OpenCASCADE technology and visualized using CAD2LIFE, our proprietary library for light CAD visualization. The CAD visualization module allows the user to navigate the 3D geometry of the pump and animate the movement of the pumps. The fluid flow itself is not rendered but the fluid chambers are colored according to the instantaneous pressure

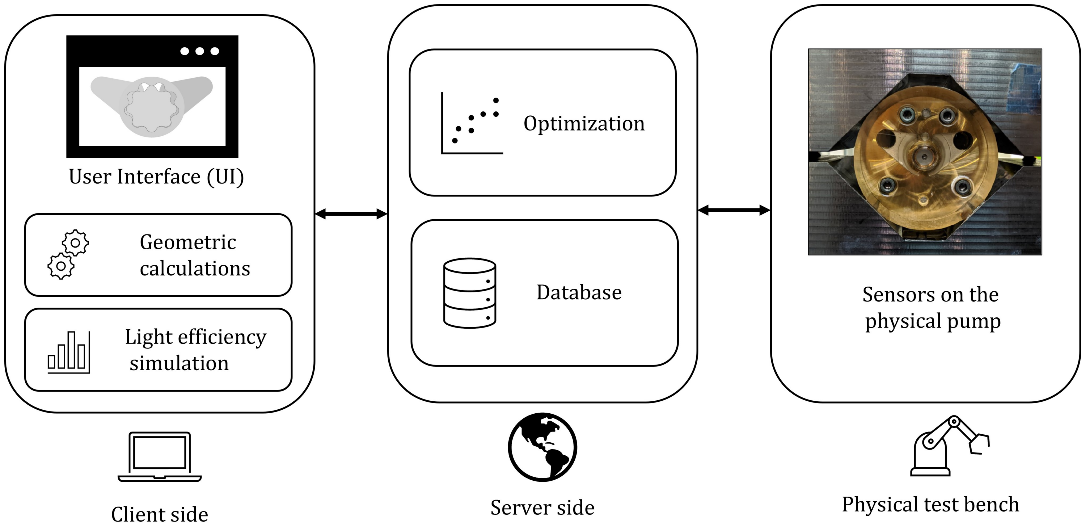

Figure 3: General architecture of the Gerotor Digital Twin

in the simulation. The objective of this module is to provide the engineer with a visual aid to judge the feasibility of a design. Data visualization is done using eCharts [Li et al. 2018], a framework for rapid construction of web-based visualizations. The light simulation of the expected efficiency (volumetric and mechanical) of the pump is done using our own algorithms designed to be fast and light yet less precise than CFD-based approaches. The details of these algorithms will be presented in an upcoming publication by the authors. Both the geometric calculations and the fluid simulations are light enough to be executed on the client side.

The server side handles the database management and the optimization routines. The database stores the geometrical data for all designs of the Gerotor and their associated performance data (both simulated and measured). The optimization routines consist of finding the geometric profile of the Gerotor that complies with a desired output flowrate while maximizing the pump's efficiency. We set up an optimization problem with an efficiency objective function and subjected to geometric constraints that express the feasibility of a design. We solve the optimization problem using a non-linear local derivative-free algorithm. These calculations are computationally expensive and therefore must be executed on the server side.

The test bench is a physical setup that operates the pump under controlled conditions and measures the variables of interest during the pump's operation. The manufactured Gerotor is connected to an electrical engine and sensors measure the pump's flowrate, input pressure and output pressure. Near real-time data capture and visualization is possible using WebSocket. The input and output pressure data could also be used to feed the simulation module and obtain the simulated efficiency in real time. The measured flowrate of the pump is compared with the simulated expected flowrate to obtain the instantaneous error of the pump's digital twin. Additionally, the torque is measured on the pump to calculate the real mechanical efficiency of the pump and compare it to the simulated value. At this moment, the communication between the virtual and the physical setup is one-way: data is sent from the test bench to the virtual model to be visualized and used in the simulations routine. In a fully-developed Digital Twin, the communication between the virtual and physical space should be two-way, thus enabling the Digital Twin to command the physical pump and change its operation conditions in real time. In spite of every effort to make a DT a friendly tool, it must be pointed out that a Digital Twin is not a pedagogical instrument. The DT allows to determine deviations of the Real Twin and viceversa. Yet, understanding of the physical process is not the central goal of a DT.

3.4 Implementation

In this section we present the client user interface of the web-based Digital Twin tool. All the functionalities of the Digital Twin tool are integrated in a single user interface structured by a panel-based configuration. Figures 4, 5 and 6 show different views of the client user interface on the web browser. Figure 4 shows the parametric design interface of the tool. This panel shows the 2-dimensional shape of the Gerotor pump defined by the parameters in the right-side panel. The geometries displayed include the internal gear, the external gear, the fluid chambers and the input and output ports. The input and output ports are automatically calculated from the geometry of the internal and external gears. Every user can tune the parameters of the pump to produce a different geometric profile and store the geometric data in the database. The 2-dimensional profile is then used to automatically generate the CAD files of the 3-dimensional model. Figure 5 shows the interactive visualization of the 3-dimensional model of the pump, along with the geometric data calculated for the pump in a full revolution. The CAD visualization panel allows the user to hide and show the different solid bodies of the assembly, change their aspect and move the viewpoint in a similar way to any CAD software.

Figure 6 shows the data visualization for the simulation module of the Digital Twin tool. The left side panel shows the scatter plot for the expected volumetric efficiency of a Gerotor profile with

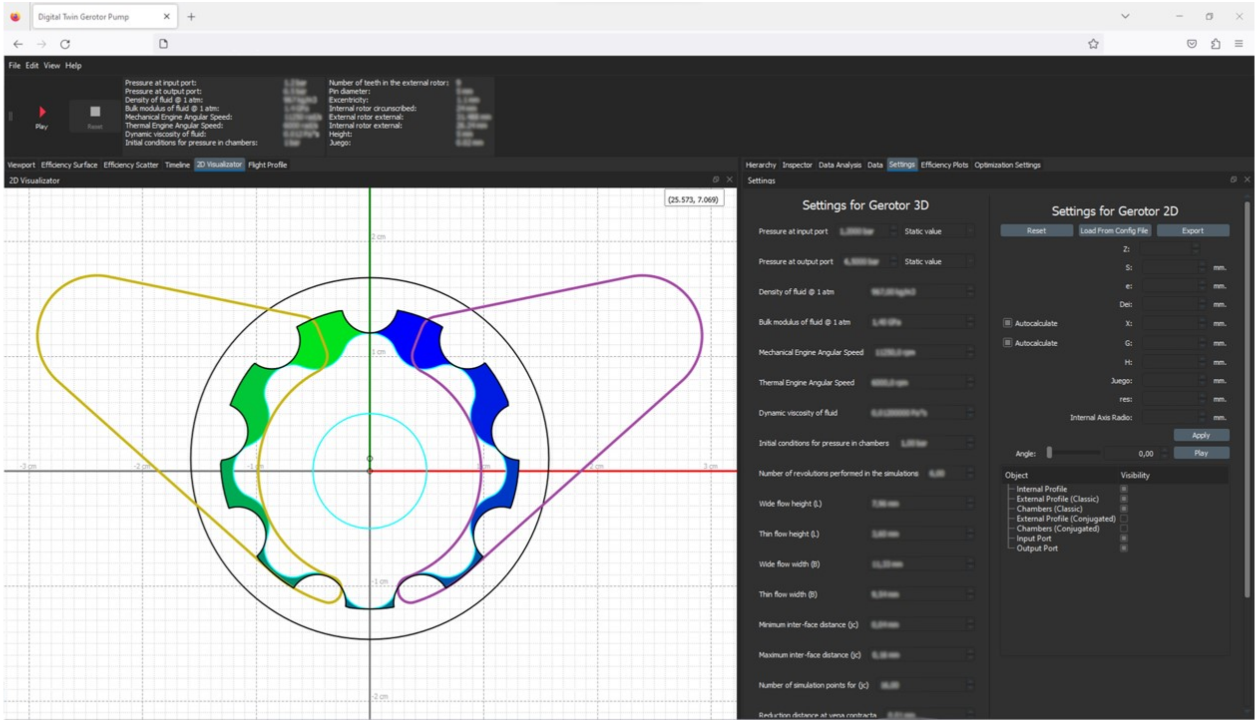

Figure 4: Gerotor design tool on the Digital Twin

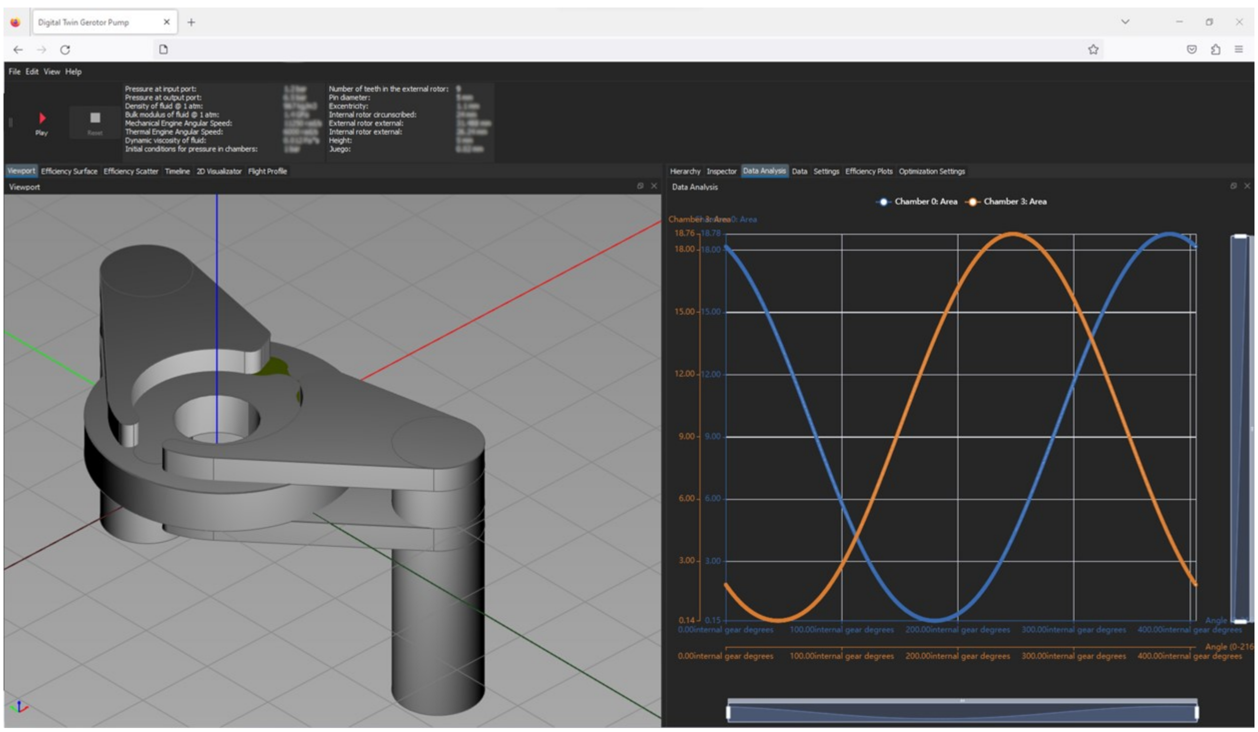

Figure 5: CAD model visualization on the Digital Twin

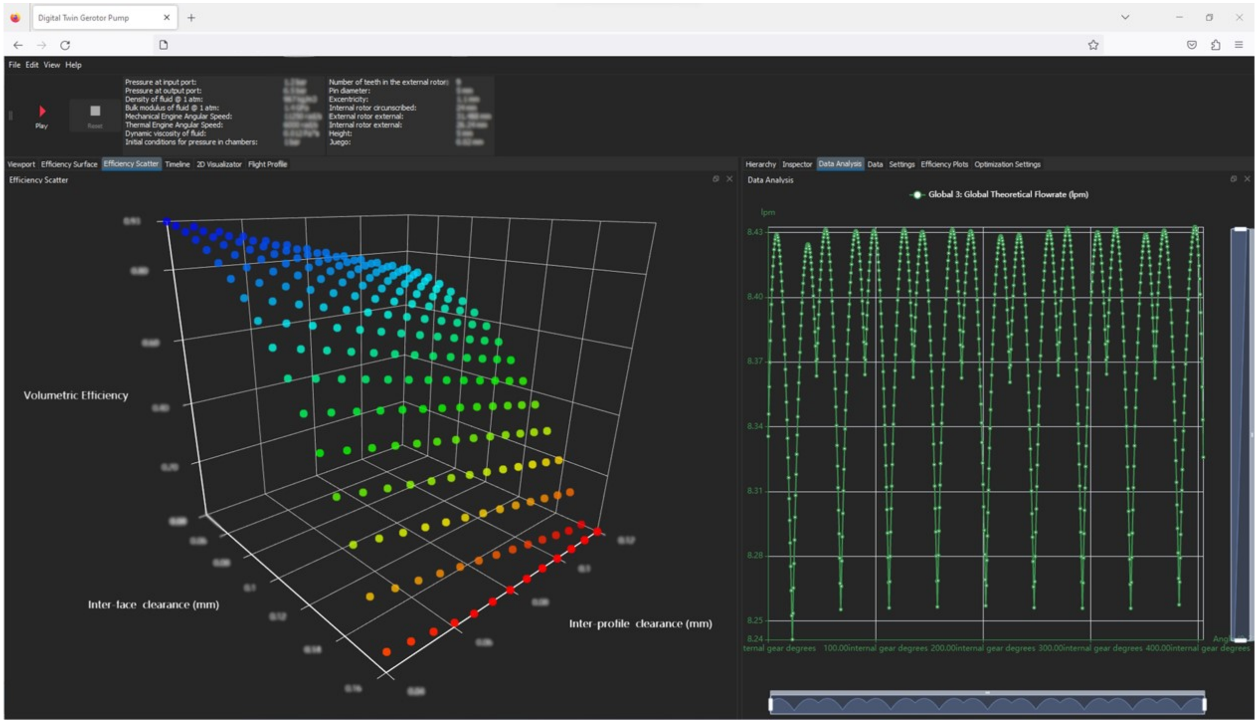

Figure 6: Simulated data visualization on the interface of the Digital Twin tool

respect to the value of the geometric clearances defined by the user. A similar plot is available for the mechanical efficiency and the overall efficiency of the pump. This simulation is performed in the client side and in under ten seconds due to the lightweight simulation routines developed by the authors. The right side panel shows the theoretical flowrate calculated by the Digital Twin using the geometric information calculated in the previous steps. All the information regarding theoretical, expected (simulated) and measured data of a particular profile is available to the user on-demand in the *Data Analysis* panel of the tool. Two additional panels, regarding the geometry optimization and lifecycle calculations for a particular profile, are not detailed in the previous figures.

In its current state, this application is intended to be used by the design engineer to accelerate the design cycle. The DT allows the engineer to predict the expected efficiency of a pump design, thus enabling the engineer to assess whether the changes introduced in the geometric profile of the pump have a positive or negative impact on the efficiency of the pump. The conclusion of whether the expected efficiency of the pump is satisfactory or not for the application at hand rests solely on the knowledge of the design engineer. This DT augments the available information on the behaviour of the pump and results in better decision making on behalf of the design engineer.

4 CONCLUSIONS AND FUTURE WORK

Physical systems can be characterized by the information they produce. A Digital Twin is a virtual entity that represents the information flows of a system and the relationships between these flows, therefore constituting a mirror copy of a physical system. These entities are every day more present in the current wave of virtualization in every aspect. Digital Twins (at least partial ones) have been produced of the human body, cities, ecosystems, industrial production lines, manufacturing machinery, amongst many others. The contemporary tendency towards geographical distribution of manufacturing and industrial knowledge opens an opportunity to use web-based services and cloud computing to enhance the capabilities of Digital Twins. As a consequence of the Internet of Things (IoT) trend, data of physical processes is more and more abundant and can be used to create more detailed and precise virtual models of the real world.

In this article we present an use case of such web-based Digital Twins for a Gerotor pump. The novelties of the present article are: i) it highlights the advantages that result from applying the Digital Twin methodology to the case of Gerotor pumps, ii) it describes the implementation of a web-based Digital Twin tool for a Gerotor pump. Our tool articulates visualization, simulation, optimization and data gathering functionalities to create a detailed model of Gerotor pumps that can be accessed by several users. The presented tool allows the user to design a Gerotor profile based on a parametric definition of the pump and visualize the geometric and performance data simulated for that specific profile using lightweight algorithms. Additionally, data from a physical test bench can be visualized in the Digital Twin to use as a comparison point with simulated data. A non-linear optimization algorithm is used to find the optimum profile for a desired output flowrate while maximizing overall efficiency of the pump. The presented tool is only an early-stage Digital Twin of a Gerotor pump. The current functionalities can be strengthened by developing more precise simulation algorithms (mantaining their lightweight characteristic) and using measured sensor data to feedback the simulation algorithms in a machine learning context.

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