

Digital Twin of Rack & Pinion Power Transmission System

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Abstract— Digital twins exist in various forms today. They are built to understand systems in greater depth. The Digital Twin is a virtual equivalent of the physical system for which it is built. Digital twins are a combination of tightly integrated software and hardware, governed by the mathematical principle of the system for which it is implemented. Digital twins are being embraced rapidly and are being widely deployed for entire systems or specific critical sub-systems to understand their entire functionality. This paper discusses about the need, scope, features and utility of Digital twins, it elaborates on the design, building and implementation of a Digital twin for a Rack and Pinion Mechanical power transmission system.

Index Terms— Digital Twin, Rack and Pinion, Mathematical modeling, Industry 4.0, Internet of Things

I. INTRODUCTION

Nearly all machines that are in use today use some kind of power and motion transmission system. The most common form is an electric motor or an Internal Combustion Engine (ICE), which typically provides rotary motion via a shaft-coupling combination.

There are many known ways to generate power but at times it is not possible to generate power where it is needed or in the right form, direction, or magnitude. This generated power / motion / energy, by the means of a power transmission system, is transferred from where it is generated to where it is required to perform work, using linkages and mechanical power transmission elements.

Rack and pinion gears are utilized to convert rotation into linear motion. This motion transfer needs to be smoothly and precisely controlled. This paper discusses the design, building and implementation of a Digital twin for a Rack and pinion power transmission system.

II. INDUSTRY 4.0

It is said that the First Industrial Revolution was the most profound revolution in human history considering the influence it had on people's day-to-day lives. It brought forth the merging of technology with industry. The acceleration in technical innovation processes, resulted in a multitude of new machinery. Major inventions and innovations aided in reshaping all pre-existing human activities in the industrial sector, in addition to making way for many new industries to form.

Industry 1.0 was all about mechanization and harnessing water and steam power. Electricity, assembly line, and mass production were the key features of Industry 2.0. Industry 3.0 introduced computers and automation. Industry 4.0 focuses on using digitalization for smart networking of machines and processes. Industry 4.0 aims to revolutionize the manufacturing process, enhance and circulate the products and services. Manufacturers are now bringing in new and advanced technologies for production operations. Industry 4.0 brings in more automation which allows for more efficient production with fewer errors. When certain operations are automated, the employees can focus on introducing more creative tasks.

Cyber Physical Systems (CPS) is at the hub of Industry 4.0 technologies. CPS is an Industry 4.0 enabled environment which implements real-time data collection and analysis, and transparency across the various aspects of manufacturing operations. Smart Factory is an example of a cyber-physical system.

A Smart Factory is a notion which is derived from Industrial Internet of Things (IIoT). It visualizes the shop level production environment as a collection of entirely automated and smart network of systems which permits facilities, manufacturing entities, the required logistics chains within the manufacturing set-up to be regulated without any manual intervention. Smart factories are equipped with sophisticated sensors, embedded software which collect and analyse data in run-time and thus results in improved decision making. Higher insights can be attained if the received data from the production operations is combined with desired operational data which else were formerly fully isolated information.

There are four pillars of the Fourth Industrial Revolution.

1. Connectivity (cloud services, blockchains, etc)
2. Artificial Intelligence and Machine Learning (big data, automation, etc)
3. Human-Machine Interaction (virtual reality, augmented reality, cobots, chatbots, etc)
4. Advanced Engineering (3D printing, nanotechnology, etc)

Industry 4.0 encompasses a set of technologies which are said to be the driving factors of Industry 4.0. They are as follows:

- Internet of Things (IoT) - is considered to be a fundamental constituent of smart factories. IoT makes it possible for the machinery to connect and communicate with other web connected devices. Due to this reliable connectivity and mechanization, it is possible to collect, analyse, and exchange large amounts of time critical data.

Cloud Computing - is the mainstay of most Industry 4.0 plan. Smart manufacturing calls for connectivity between machines and the integration of verticals like, engineering, supply chain, production, sales, distribution, and service. Characteristics of Cloud Computing can help meet most of these demands. Additionally, cloud can aid a more efficient and cost-effective processing of large amounts of data for storage and analysis.

Cloud computing can also prove beneficial to small and medium sized companies by reducing startup costs, given that they can administer their needs and scales according to their growth.

- Artificial Intelligence (AI) and Machine Learning (ML) - allow manufacturing companies to take full advantage of the amount of information created. This is favorable not just on the shop floor, but also across other business units, as well as from associates and third-party authorities. They can help build insights which provide visibility, predictability and automation of processes.

For example, predictive maintenance of machinery based on ML algorithms can be performed to reduce disruptions in processes, ensuing higher up-time and superior efficiency.

- Computing at the Edge - The requirement of monitored production operation means that preliminary data analysis must be performed right where the data is generated (at the edge). This minimizes the data transmission between where data is produced and where a response is required.

Computing at the edge ensures that data stays near its source, thus also reducing security risks.

- Digital Twin - Digital transformation has facilitated companies to build digital twins. Digital Twins are the virtual replicas of entities involved in the manufacturing process. Digital twins help amplify productivity, enhance workflows.

III. DIGITAL TWIN

The world is currently undergoing a massive digital transformation, also known as Industry 4.0. Digitalization is booming in all stages of manufacturing and has taken the industries by a storm. This presents manufacturers with all new opportunities to increase productivity.

Among the top by-products of the Fourth Industrial Revolution are Digital Twins.

They are one of the definitive methods for improving system design, testing, and maintenance is achieved through modeling and simulation [1]. Modeling and simulation play a conclusive role in aiding design operations and validating system characteristics.

A digital twin is a virtual model designed to accurately represent a physical entity. Digital twins are regularly updated based on data in real-time and use simulation, machine learning, and reasoning to aid decision making [2].

There are four types of digital twins [3]:

1. Component Twins - digitally represent a singular segment of the whole system.
2. Asset Twins - The term “Asset” refers to two or more components that work together as a part of a more extensive system. Asset twins are used to digitally represent how those components operate together.
3. System Twins - Building upwards from Asset twins, System twins are obtained. System twins are adopted to illustrate how various assets work together as a part of a more comprehensive system.
4. Process Twins - are used to depict the virtual environment of the whole object and to gain insight into the operations of all its various components, assets, and units, which typically provides rotary motion via a shaft-coupling combination.

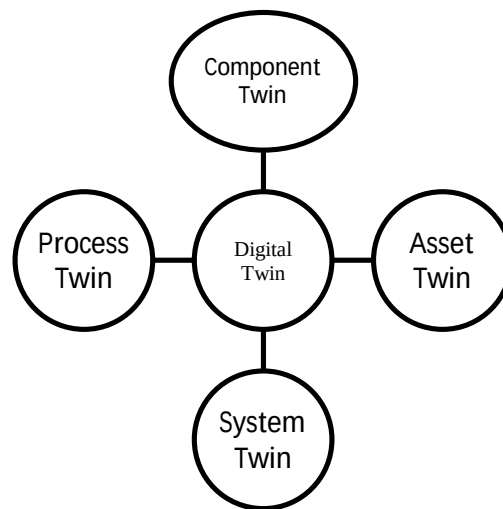


Figure 1. Types of Digital Twins

The idea of digital twin technology was voiced in the year 1991, by David Gelernter in the publication of Mirror Worlds. Dr. Michael Grieves holds the credit for implementing the concept of digital twins in manufacturing in 2002 for the first time and formally announcing the digital twin software concept. Later on, in 2010, the phrase “Digital Twin” was proposed by NASA’s John Vickers [3].

However, the idea of digital twins is not entirely new although it may seem otherwise. This concept actually dates back to the 1960s. It is said to have originated at NASA when they used it as a “living model” for their Apollo mission. As a response to Apollo 13’s failure, NASA engaged numerous sensors to evaluate the damages and extended a physical model (a mirrored system) of the craft to incorporate digital elements. This “digital twin” was the first of its kind. It allowed for a continuous consumption of data which helped in modeling the events preceding the accident for forensic analysis and deciding future actions. Hence, it can be rightfully stated that NASA has pioneered the use of digital twins.

The sample entity is equipped with several sensors that collect real-time data about the various aspects of the entity’s performance. This data is then forwarded to a processing system to be applied to its digital model. Once the virtual model is acquainted with the data collected by the sensors, it can be used to run simulations regarding the object’s performance. Upon studying how the entity performs during virtual simulation, complications can be identified and possible improvements can be generated. These improvements can then be applied to the physical entity.

While digital twins may sound similar to simulations, they do differ in quite a few parameters. The main difference is that digital twins require a physical aid and a sensor network, whereas simulations do not. Digital twins also possess many other advantages over simulations such as their ability to run multiple simulations at once, having a virtual environment, and working by a two-way data flow. These perks make them comparatively richer for study. Hence, it can be said that digital twins bridge the gap between physical entities and digital entities.

IV. APPLICATION DOMAINS OF DIGITAL TWINS

Nearly all machines that are in use today use some kind of power and motion transmission system. The most common form is an electric motor or an Internal Combustion Engine (ICE), which typically provides rotary motion via a shaft–coupling combination.

These days' industries primarily use the digital twin technology to obtain meticulous virtual representations of physical entities and simulations of their working processes. Following are some of the industries that have benefitted from the employment of digital twins:

- **Product Designing** - The digital twin technology provides a virtual prototype of a physical asset. It gathers necessary data from sensors and grants the ability to design, construct, test, and validate predictive analysis and automation. Testing on the virtual replica instead of a physical prototype can help in cutting down on production costs, time, and the number of prototypes. The data collected over time can be implemented for enhancing product quality, customization, usage, etc.
- **Manufacturing** - Since digital twins are made to replicate the lifecycle of any product, it definitely is of plentiful help in the manufacturing sector regarding optimization of processes. Digital twins can help in administering a product in its initial and final phases, as well as every phase in between.
- **Aviation** - It is known that the origin of the idea of digital twins was in the aerospace sector. Digital twins are mainly used for predictive maintenance, digital support, diagnostics, and optimization. This in turn helps in reducing the amount of cost and time for development as well as maintenance.
- **Smart Cities** - Digital twins reportedly have far-reaching utilizations in the case of smart city network development projects. They can be counted upon to prove extremely beneficial in this area. IoT enabled sensors can be used to collect the data necessary for creating futuristic AI algorithms. These algorithms can be used in management operations regarding roads, buildings, logistics, public services, etc.
- **Construction** - Use of digital twins in the construction industry can help in reforming and reimagining projects. Through digital twins, employees can monitor the process, identify probable threats, and make necessary adjustments while also ensuring that the project is completed on time and is within the budget, without compromising on the quality.
- **Healthcare** - The healthcare industry has limitless opportunities of application of the digital twin technology. In the healthcare sector, digital twins were initially used for medical devices regarding predictive maintenance and performance optimization. The sensor-generated data used by digital twins can also be applicable in tracking various health indicators. This technology can be useful in predicting the occurrence of an illness based on medical history, clinical research, personalized medicine, drug development, behaviors' of organs, testing and research on human anatomy, etc.
- **Automotive** - In the automotive industry, digital twins can be used to replicate all sorts of complex, co-functioning systems in auto design in order to enhance vehicle performance and upsurge efficiency encircling production.

The above are a sample of industries that have the need of employing digital twins. In addition to these, the industries dealing with utilities, agriculture, retail, education, IoT applications, mining, maintenance operations, etc could also potentially benefit from adopting digital twins.

V. RACK AND PINION POWER TRANSMISSION SYSTEM

Rack and Pinion is a mechanical device. It consists of two elements - a rectangular toothed bar and a circular wheel. The straight-line gear is called the rack, whereas the circular gear is known as the pinion.

In this mechanism, the teeth of the rack are made to mesh with the teeth of the pinion. It is observed that the rack is driven in a straight path while the pinion is rotated. The rack and pinion mechanism is used to convert rotational motion into linear motion and vice-versa.

The Rack and Pinion system consists of two gears, the circular pinion, and the rectangular rack. Both the gears have teeth that mesh with each other to transmit power. In this combination, since the two gears engage with each other, rotating the pinion will cause the rack to be driven in a line. The opposite is also true, meaning that when the rack is moved linearly, the pinion will rotate [4]. It is depicted as a schematic in Figure 2, and in detail in Figure 3. In (a) the rack will move along the path indicated by AB, in (b) the pinion rotates and moves along the path indicated as CD in Figure 3.

This system is needed in cases where rotational motion is to be converted into linear motion or vice versa. There is also a reduction in the number of gears which is a plus point.

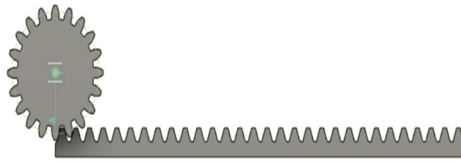


Figure 2 The schematic of Rack and Pinion system

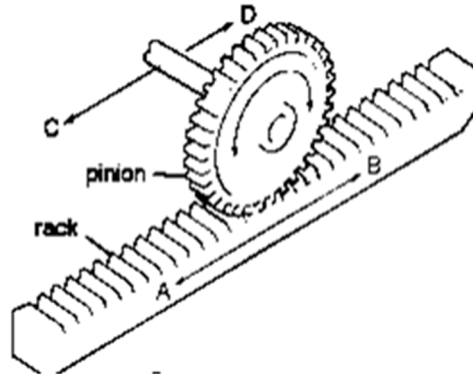


Figure 3 Details of Rack and Pinion

Image Credit - <https://images.app.goo.gl/mdaZqLBKN8GQbWm88>

There are two variations commonly employed for this mechanism,

- a. the pinion rotates about a fixed axis, the rack will translate
- b. the rack is fixed and the pinion rotates

VI. MATHEMATICAL MODEL OF RACK AND PINION

The mathematical equations governing the movement of the Rack and Pinion system,

Module = 2mm

Pressure angle = 20 degrees

Number of Teeth = 30

Overall length of the Rack translated

= $(\pi * \text{Module} * \text{Number of Teeth}) \text{ mm}$

= $3.14 * 2\text{mm} * 30$

= 188.4 mm

Back thickness = 5mm

Width = 20 mm

VII. IMPLEMENTATION OF THE DIGITAL TWIN FOR RACK AND PINION

The digital twin implementation of the Rack and Pinion system has the following details,

The software details are as follows,

- The 3D representation is designed using Tinker CAD software
- The movement and control is implemented in Blender software with interface and scripting (programming) done in Python.

The hardware details are as follows,

- The interfacing is done with the Arduino microcontroller with a Wi-Fi shield for communication.
- For the circular motion of the Pinion a DC motor is used with L298N motor driver with Arduino.
- The Pinion also has a hand crank lever for manual rotation.
- For the linear motion of the Rack the H bridge, Linear Actuator with an feedback potentiometer is employed.
- The Rack can also be moved by Hand.

The Linear Movement (Translation) of the Rack is governed by the mathematical equations given above. Any linear movement beyond the specified limit is not possible as it is constrained by the software.

The Rotational motion of the Pinion is also governed by the mathematical equations given above. Any rotational movement beyond the specified limit is not possible as it is constrained by the software.

The actual implementation has two variants of operation, as depicted in figure 4.

- a. The pinion rotates about a fixed axis, the rack will translate, the Motor is actuated as required and the Rack displacement is observed and checked. This can be done manually too using the crank lever to rotate the Pinion.
 - b. The rack is fixed, and the pinion rotates, the rack is moved using the linear actuator and the Pinion circular motion is observed and checked. This can be done manually too by moving the Rack in the desired direction.
- The implementation can be viewed in run-time on the dashboard of the Blender software.

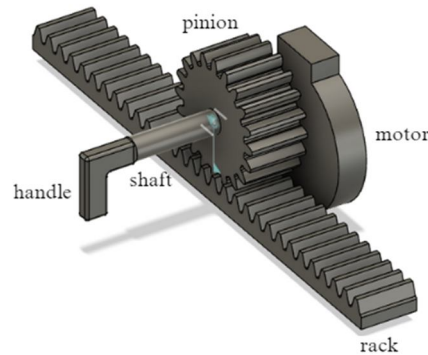


Figure 4 The complete setup

VIII. CONCLUSION

Digital Twins are an elaborate way to prepare the virtual representation of the physical device which it represents. Digital twins are tightly coupled with the physical machine / system which they represent. This paper explained about the need, scope, features and utility of Digital twins, it elaborates on the design, building and implementation of a Digital twin for a Rack and Pinion Mechanical power transmission system.

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