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INNOVATIVE DESIGN SOLUTIONS OF GEAR TRANSMISSIONS FOR INDUSTRY 4.0

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Abstract: Gear transmissions are relatively simple mechanisms whose quality, price, delivery time and design appearance are almost equal. This is the common reason why it is very difficult for all gear manufacturers to ensure the successful placement of their products on the market. However, regardless of their simplicity, gear transmissions may have different design and technical solutions, and due to different limitations of individual components, the calculation of load capacity and other technical characteristics can be quite complicated. In accordance with the basic settings of Industry 4.0, smart transmissions are being developed that will be able to provide a certain advantage over the competition and thus, for sure, ensure the successful business of these innovative companies. This paper describes the basic principles of construction using new technologies, primarily using the Internet of Things and digital twins. The paper includes an analysis of approaches to the creation of Digital Twins. Describe why Industry 4.0 is so different and specific, define what is Cyber–physical systems and the Internet of Things, and what is predictive monitoring with using different sensors.
Keywords: Innovative design, Gear transmissions, Digital twin

INTRODUCTION

Due to the very strong competition, all gear manufacturers are trying to create some advantage over the competition in order to improve the placement of their products on the market. Many manufacturers try to attract customers by short delivery times. Other manufacturers try to achieve this with high quality, although there are also manufacturers who try to obtain customers with low prices (which is achieved with either cheaper labour, a more favourable conceptual solution, or slightly lower quality of their gearboxes). Of course, some manufacturers obtain customers with a high–quality level of gear transmissions and also with a more attractive appearance of their gearboxes. [1]

Gears, depending on their application, have different dimensions, design, technical characteristics, as well as different damages, failures and limited conditions under which they are determined. They are certainly among the most complicated mechanisms for calculation, design and construction and have a very important and general significance in modern mechanical engineering. [2] Modern solutions of universal helical gearboxes are characterized, first of all, by large torque capacity and high values of gear ratio in the frame of relatively small overall dimensions of the gear unit. [1]

The rapid development of information and communication technologies (ICT) has led to the development of the fourth industrial revolution, i.e. Industry 4.0, which is based on the use of information and communication technologies (ICT) and their communication using the Internet. This brings additional new components that are necessary for modern power transmissions, and without which it is impossible today to perform modern design, production, supervision and maintenance.

IMPLEMENTATION OF INDUSTRY 4.0 AS A MODERN DEVELOPMENT OF GEAR DRIVES

Industry 4.0 offers huge potential for improvement and success not only in the field of gear drives production but mostly for product innovation. Efficient engineering of the new generation of smart products and services is appeared, as well as new business models that are used in their marketing. In order to be able to successfully use this potential, manufacturers are facing a great process of transformation, i.e. cardinal changes where they have to overcome many challenges.

The focus of these changes is mostly related to process models, methods, IT tools and information models in the development of smart products and services. The development of products and services is the most important phase of engineering since in this phase lies the greatest innovation potential and the characteristics of future products are determined here. [3]

The essential goal of Industry 4.0 is to make manufacturing, but also related industries (e.g. logistics) faster, more efficient and more related to customer, while at the same time going beyond automation and optimization and detecting new business opportunities and models. In that way, personalization and customization of gear drive manufacturing will be established.

The fourth industrial revolution arose in the correlation between the existing traditional industry and innovations in the field of the Internet, i.e. in the field of information and communication technologies (ICT).

Innovations based on ICT can be divided into five categories (Figure1):

- Internet (Internet of Things, Internet service, ...);
- Hardware (smart devices, cloud computing, augmented reality, ...);
- Software (service–oriented architecture, semantic and Big–Data technologies, ...);
- Communication (5G, WiFi, ...);
- Built–in microsystems (microprocessors, microsensors, microactuators, ...). [3]

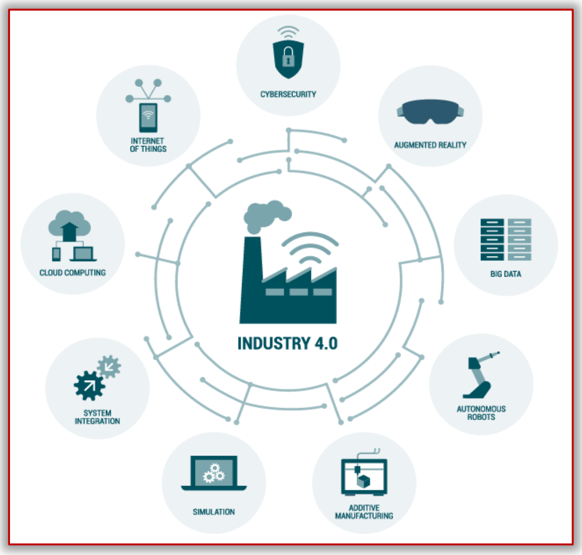

Figure 1. Industry 4.0 – the digital transformation

Trends in the development of modern technical facilities and their production largely refer to the ideology of Industry 4.0, in which a key role is played by the development of the sensor base and intellectualization of machines and materials [4], the Internet of things (IoT) and the creation of digital twins of items.

Industry 4.0 is characterized by much better automation, the bridging of the physical and digital world through cyber–physical systems, enabled by Industrial IoT. A central industrial control system is shifted to one where smart products define the production steps, there are closed–loop data models and control systems and personalization and customization of products are applied.

The basic structure of industrial products (BMS), in this case, gear transmission, consists of mechanical components (gears, shafts, bearings, etc.) (Figure2). In further evolutionary development, this structure was supplemented by electronic components and software, thus creating mechatronic products (MP). As a result of the development of miniature microcomputers and further software development, mechatronic products were equipped with artificial intelligence, so intelligent mechatronic products (IMP) appeared. In the next evolutionary step, products are enhanced by the ability to communicate with other products and the Internet. These products are called "Cyber–Physical Systems" (CPS). [3]

Cyber–physical systems define the basis of Industry 4.0 (e.g., smart machines). They use modern control systems, have embedded software systems and dispose of an Internet address to connect and be addressed via the Internet of Things (IoT). [6]

The cyber–physical systems are the basis and enable new capabilities in areas such as product design, prototyping and development, remote control, services and diagnosis, condition monitoring, proactive and predictive maintenance, track and trace, structural health and systems health monitoring, planning, innovation capability, agility, real–time applications and more. [6]

Since the Industry 4.0 is the next new stage in the organization and control of the value chain across the lifecycle of products, this ongoing improvement in which CPS fits started from mechanical systems and moved to mechatronics (where controllers, sensors and actuators are used) and adaptronics, and is now entering this stage of the rise of cyber–physical systems.

Cyber–physical systems result to new possibilities in areas such as structural health monitoring, track and trace, remote diagnosis, remote services, remote control, condition monitoring, systems health monitoring and so forth. [6]

Characteristics of cyber–physical systems:

- CPS represents an evolution in manufacturing, mechanics and engineering because they provide digital and physical bridging of system components, which is possibly thanks to Internet technology, and the bridging/convergence of Information Technology and Operational Technology;
- CPS can communicate since they have intelligent control systems, embedded software and communication capabilities as they can be connected in a network of cyber–physical systems;
- CPS can be uniquely identified because they dispose of an IP (Internet Protocol) address which means that they use Internet technology and are part of an Internet of Everything in which they can be uniquely addressed (each system has an identifier);
- CPS must have controllers, sensors and actuators (but this was already the case in previous stages before cyber–physical systems in mechatronics and adaptronics);
- CPS are the basic building blocks of Industry 4.0 and the enablers of additional capabilities in manufacturing such as track and trace and remote control;
- Smart factories, smart logistics (Logistics 4.0) and other smart areas of applications are enabled by cyber–physical systems.

Industry 4.0 offers multiple benefits for the production of gear transmissions. Central requirements from gear drive production are increased productivity, flexibility, quality and speed production (Figure 3). One of the first goals of

Industry 4.0 is productivity through optimization and automation. In other words: saving costs, increasing profitability, reducing waste, automating to prevent errors and delays, speeding up production to work more in real–time and in the function of the overall value chain, where speed is crucial for everyone, digitizing paper–based flows, being able to intervene faster in case of production issues.

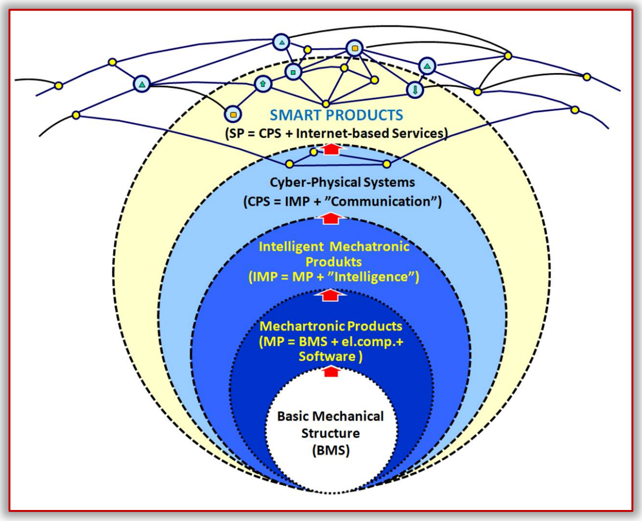

Figure 2. Evolution of stages from machine products (BMS) to smart products (SP) [5]

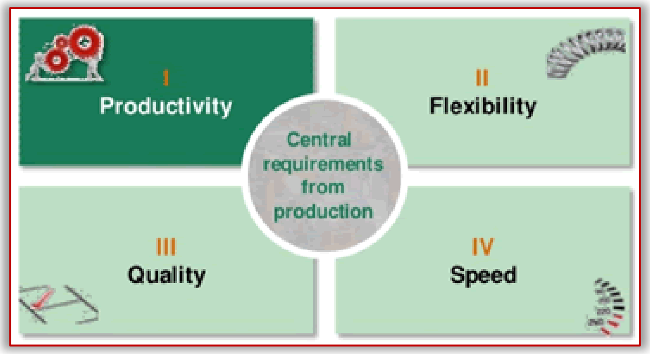

Figure3. Industry 4.0 offers multiple benefits for production

Productivity increasing of gear drives can be obtained by using a higher level of automation that reduces production time and enables better asset utilization and inventory management. The flexibility of gearbox manufacturing can be realized through machines and robots that can execute the production steps for a large number of products. Sensors and actuators that monitor the current production in real–time and quickly intervene in case of errors increase gear transmission quality. Production speed is increased by using consistent data and, e.g. new simulation opportunities.

There is also improvement of manufacturing conditions. For example, occupational safety is improved through increased automation. Ergonomically adapted workstations offer better working conditions. Increased collaboration in the product network is the result of consistent data availability. Environment is better protected by using optimized use of resources (e.g., more energy–efficient operation of machinery). Inovative capability is increased through new technological possibilities in manufacturing.

New generations of automated sensors connected to the Internet and supported by developed hardware and software tools enable the creation of fully digitalized factories. Industry 4.0 has already been introduced in many countries, thus ensuring the survival of the industry and its competitive development in modern conditions. Modern digital technologies such as the Internet of Things (IoT), robotics, cloud computing, cyber–physical systems and scalable big data analytics are key to implementing the Industry 4.0 concept. Industry 4.0 implies complete digitalization of all production processes and application of the mentioned digital technologies when creating an idea about a product, product engineering, production organization, production realization, process control and provision of industrial services. [4]

INTERNET OF THINGS AND INDUSTRY 4.0 AT GEAR DRIVES DEVELOPMENT

Trends in the development of modern technical facilities and their production largely refer to the ideology of Industry 4.0, in which a key role is played by the development of the sensor base and intellectualization of machines and materials, the Internet of things (IoT) and the creation of digital twins of items.

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The Internet of Things (IoT) is a new type of communication between intelligent devices. Practically, a parallel internet is being created in which things communicate with each other, exchange information, manage each other, react and influence the environment in which they find themselves, without the influence of people. [3]

The presence of an IP address by definition means that cyber–physical systems, as objects, are connected to the Internet (of Things). An IP address also means that the cyber–physical system can be uniquely identified within the network. This is a key characteristic of the Internet of Things as well.

Cyber–physical systems are also equipped with sensors, actuators and all the other elements which are part of the Internet of Things. Cyber–physical systems, just like the Internet of Things need connectivity.

The Internet of Things consists of objects with embedded or attached technologies that enable them to sense data, collect them and send them for a specific purpose. Depending on the object and goal this could be capturing data regarding movement, location, presence of gasses, temperature, 'health' conditions of devices, the list is endless. [7]

IoT devices can also receive data and instructions, again depending on the 'use case'. All this applies to cyber–physical systems as well, which are essentially connected objects. There are more similar characteristics, but there are already many common things.

The Internet of Things focuses on looking for all the influences that surround a machine system to provide the right hardware and software to give this system a market advantage. In Industry 4.0, technology is required to be more scalable and flexible enough to respond well to changes in the supply chain as well as the entire product line. The main difference that makes both IoT and Industry 4.0 technologies key components of advanced industry transformation is connectivity. IoT seeks to connect everything to the Internet, and Industry 4.0 describes the idea of connecting sensors, actuators, control units, logistics services, other planning systems, and so on. [4]

Because data–intensive industries require secure and reliable technology that is capable of storing and processing data in the cloud for better availability.

The advanced companies that introduced Industry 4.0 strive to manage their business remotely to achieve better results in an economical price structure. IoT allows remote monitoring of each device in real–time. It also keeps data secure and requires less manual work through all of these operations.

Machine systems are required to have efficient tools or systems that help manage big data and use it to infer outcomes based on different situations. IoT technology includes sensors and advanced connections of all components that are controlled and monitored. This way of connecting enables quick answers and better decision making at the right time.

The Internet of Things promotes effective machine system management strategies and improves their performance thanks to a constant control system. This helps to reduce their workload through manual handling of each task and to automate the entire industrial processing. Thus, it leads to relatively simpler maintenance of the device and simplifies the decision–making process.

MAJOR DIFFERENTIATORS OF IoT AND INDUSTRIAL IoT

The term internet of things (IoT) is often used these days. This technology is nothing but smart devices that are having good connectivity and can communicate with each other seamlessly. The number of IoT devices is growing exponentially with each passing day.

An almost identical term used is Industrial IoT (IIoT). Although both of these terms sound almost the same, because they are both based on the same technology and depend on the interconnection of devices, there are significant differences in these two concepts. [7] IoT is usually used by consumers, and as the name suggests, industrial IoT is for industry, such as manufacturing, transportation, etc. Table 1 shows the basic differences between these two terms.

Table 1. Differences between IoT and Industrial IoT [7]

Points of distinction	IoT	Industrial IoT
Security	Not critical	Is a crucial element
Scalability	Limited data processing	Support large scale network
Development focus	To improve consumer convenience	To make industrial operations efficient and effective
Interoperability	Not much integration required	Integration with legacy Operational Technologies
Precision	Can be close to accurate	Should be accurate

In the IoT interconnected system, safety is not a huge deal because consumer data does not require any security. The security of industrial IoT is becoming a key element when it comes to data entry and transmission. The disruption of production systems that involve industrial IoT costs huge financial resources and disrupts the economic activity of a large number of people and processes. Therefore, industrial IoT solutions consist of a series of advanced security measures, using security and resilient system architectures, encryption and authentication, specialized chipsets and threat detection.

Industrial IoT solutions must coexist with older operating technologies such as SCADA, M2M and other production execution systems. It is difficult to make older operating technologies disappear quickly. Industrial IoT will replace them, but to do so, it must first integrate with them, so industrial IoT solutions must support different protocols and datasets. [7]

In the contrast to IoT solutions, the Industrial IoT solutions must be very precise and accurate. From data entry to analysis, accuracy and precision should not be compromised because the automatic high–speed, high–volume manufacturing processes are synchronized to milliseconds. The quality assurance systems detect small dimensional variations in the data and take an immediate course of actions which are entirely dependent on those measurements. In the Industrial environment, "close enough" isn't good enough, and can cause downtimes, which ultimately results in lost revenues or loss of life.

DIGITAL TWINS – A CRITICAL MILESTONE TOWARD THE SMART INDUSTRY

Although the concept of a digital twin exists for quite a time, only thanks to the Internet of Things (IoT) it has become cost–effective for implementation.

Simply, the digital twin is a virtual model of a process, product, or service. This pairing of the virtual and physical worlds allows data analysis and system monitoring to solve problems before they even occur, prevent downtime, develop new features, and even plan for the future using simulations. [8]

The digital twin of an item is a computer image corresponding to a real one. It is created for each item during the design process, and then the digital twin is detailed during the production of the item and becomes its exact (in the ideal case) digital copy, which allows the reproduction of all the basic properties of the item. Then the digital twin goes through all the stages of the life cycle of a physical object.

Since the gear transmissions are among the most difficult mechanisms to calculate and design, the methods of their calculation, design and diagnostics have a general significance in machine building. Certainly, it is unrealistic to use a single and universal model that describes all the properties of a technically complicated mechanism, such as gear transmission.

Creating a digital twin based on a set of models and methods that reflect the transmission behaviour as a whole in functional and reliable aspects (lifetime mechanics) is an effective way to solve the problem of transmission design and maintenance during its life cycle. [2]

The central concept of Industry 4.0 is a cyber–physical system (CPS), which is characterized by a physical object, for example, a machine, and its digital twin, in the form of a model or a set of models that are implemented in software simulating the behaviour of the physical object.

Fundamentally, new parts in Industry 4.0 are components that are largely developed in mechanics. The most important ones are the model approach and the digital twin of the product, as well as sensor bases, wireless data transmission, diagnostics and analytics.

Digital twins are ready to transform manufacturing processes and offer new ways to reduce costs, monitor assets, optimize maintenance, reduce downtime and enable the creation of connected products.

Faults and defects of mechanical transmissions increase costs and overload employees in the production process. To alleviate these problems, manufacturers can use the digital twin, as one of the Industrial IoT functions. The digital twin replicates the mechanical transmission during its development into digital form. By upgrading the sensors, manufacturers collect data on the entire working mechanism of their equipment and the expected output of each unit. The data entered from the digital model allows manufacturers to analyze the efficiency, effectiveness and accuracy of the system. It also helps identify potential congestions in the production of a mechanical transmission, which helps the manufacturer create a better version of the product. [9]

The digital twin can allow companies to have a complete digital footprint of their products from design and development through the end of the product life cycle. This, in turn, may enable them to understand not only the product as designed but also the system that built the product and how the product is used in the field. With the creation of the digital twin, companies may realize significant value in the areas of speed to market with a new product, improved operations, reduced defects, and emerging new business models to drive revenue.

The digital twin may enable companies to solve physical issues faster by detecting them sooner, predict outcomes to a much higher degree of accuracy, design and build better products, and, ultimately, better serve their customers. With this type of smart architecture design, companies may realize value and benefits iteratively and faster than ever before. [10]

APPROACHES FOR CREATING DIGITAL TWINS

Three approaches can be distinguished when creating digital twins.

- The first approach considers general methodology for any field of application. The main tool is the use of big data and analytics. This approach is mainly used to improve items that have relatively short lifetimes. At the same time, models of workflows of items are not considered in detail. So, in one paper [11], operational data is used to improve the production process and service. Another paper [12] considers the possibility of applying operational data to the design process. Digital twin–driven product design (DTPD) is proposed and analyzed. DTPD is expected to be most useful for the iterative redesign of an existing product instead of a novel design or a completely new product.
- The second approach is based on the use of universal methods and software based on certain physical (mechanical, etc.) models. At the same time, modelling the workflow of an item is widely used. To simulate the behaviour of items, the finite element method and methods of multibody dynamics are widely used. Siemens AG gives typical examples of the second approach.

The digital twin can be considered as the virtual copy of a real–world asset. It integrates here with all data, models and other structured information related to the product, plant, infrastructure system or production process. This data can be generated during design, engineering, manufacturing, commissioning, operation or service. The fast adoption of the digital twin concept builds on advances in simulation methods, computing power, availability of IoT data and artificial intelligence. [13]

Two key elements of the digital twin are that it is holistic and dynamic. Holistic implies that all information is integrated and consistently consumed at various parts of the life cycle, connected through a digital thread. Dynamic implies that the digital thread grows over the life cycle, completing the system description and adding higher levels of detail when these become available and updating the underlying models based on the actual product use.

At its highest level, a digital thread is a continuous, seamless strand of data that connects each stage of the product life cycle from design, to build, to in–the–field usage. It provides, in effect, the channel through which data about the product travel. Such data—their storage, ready access, modelling, and analysis—are what create the ability to model production and drive efficient supply chain communications. [10]

- The third approach includes special models and methods related to specific objects. In this case, these are gears and transmissions.

Some papers give different modern representations of digital twins in the field of gears and transmissions. A paper [14] describes a simulation–based model meant to predict the fatigue endurance of tooth root. The model can be regarded as a digital twin of performance and enables the prediction of the fatigue behaviour of tooth roots even for conditions which are not covered by the standards yet.

One publication [15] describes an efficient and goal–oriented way, which presents the immense advantages of the use of digital twins, shown in the example of spur gear stage design, the definition of macro geometry and the final microgeometry optimization of the tooth flank.

Another paper [16] points out that nowadays a large number of different CAE tools are available for the design and analysis of a gear unit and its components, each of which has its own strengths. A major milestone for Industry 4.0 is the establishment of industry–wide standards. The German Research Association for Drive Technology (FVA e.V.), in close cooperation with industry and research, is developing an industry–wide standard for simple data exchange in transmission development under the name REXS (Reusable Engineering EXchange Standard). The REXS initiative pursues the goal of providing a "digital twin" in transmission development and calculation. REXS defines uniform parametric modelling and nomenclature of gear units and their components across standards and industries, based on detailed terminology from FVA's 25 project committees and 50 years of joint industrial research.

This is meant to reduce the number of interfaces involved in the design process. This is the vision of the REXS initiative: a free, nonproprietary, standardized interface for the exchange of transmission data which reduces the complexity of data exchange in the design process significantly (Figure 4).

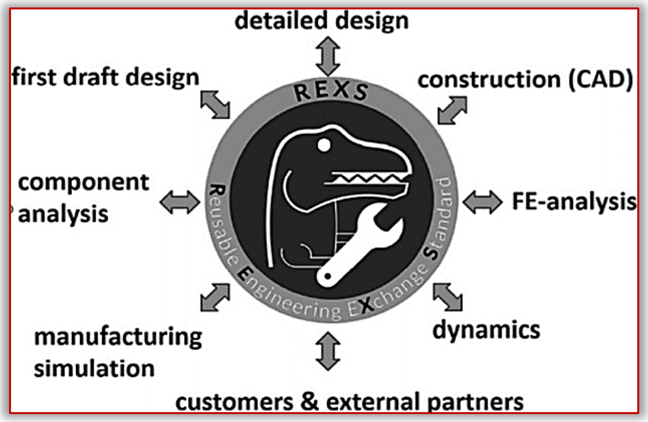

Figure 4. Design process with standardized interface REXS

REXS has the potential to establish itself on a large scale as a standard model for data exchange in the field of gear unit design and analysis. This would result in several advantages for the software manufacturers, for the companies using the tools and for the users:

- Transmission designs and analyses at any level of detail, i.e. from the overall system view via the analysis of individual components to the individual physical phenomena, can always be carried out based on a single data model;
- A simple data exchange between classic analytical gear design programs and universal dynamic, FE and CAD systems would be possible. Expenses for additional, specific modelling could be greatly reduced, etc.

VISION AND UNDERSTANDING OF THE "DIGITAL TWIN"

The following aspects are essential:

- Each part of the machine is represented as a source of information signals;
- The machine units in which it is possible and appropriate to implement the principles of reflexive control are allocated; procedures for the identification of information sources, control objects and reflexive nodes are provided, then their interdependences are determined.

The information model should be designed in such a way as to allow the use of various sources: semantic, structural (logical), parametric (quantitative, mathematical) models; measurement results; expert evaluations; means of simulating the elements and units of the machine (in slow, accelerated and real time scales in relation to the current, retrospective and predicted state).

Thus, the developed methodology anticipated one of the principles of Industry 4.0: the creation and use of an item's digital twin.

The assumption that there are possible conflicts among the subsystems of the machine, endowed with intellectual properties, can be considered as a forecast for the forthcoming Industry 4.0 technologies.

Modern authors' conception is depicted in Figure 5 [17]. This concept is presented in detail below in relation to gears and transmissions.

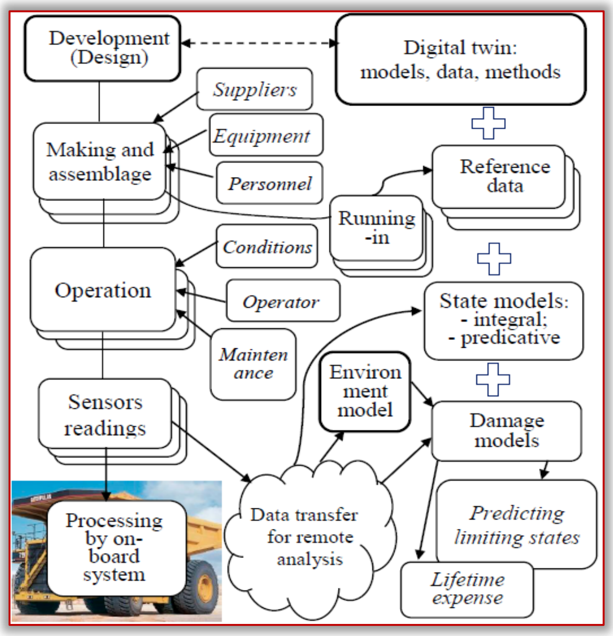

Figure 5. Evolution of the item and its digital twin during life cycle [17]

Fortunately, software tools are rapidly rising to the challenge of concurrently building and integrating digital twins. As the technology evolves, those tools will grow more powerful and sophisticated, and IoT–enabled digital twins will become more tightly integrated into a plant's production processes, and far more capable.

They will also become smarter, using machine learning programs, a type of artificial intelligence, to learn more about a factory's machines and improve the ability of digital twins to simulate and predict their behaviour.

As artificial intelligence systems learn more about specific machines, they will use their digital twins to help engineers run plants more efficiently. If there is some problem with a machine, artificial intelligence can analyze it to see what is wrong. The better the artificial intelligence knows the machine, the more accurately it can predict when that failure is likely to happen. [18]

The growing importance of digital twins in IoT projects today de facto is mainly mentioned in the scope of the manufacturing sector, the bridging of digital and physical worlds in Industry 4.0, the digital transformation of manufacturing and industrial markets overall, including smart supply chain management. As written previously, the usage of the IoT in manufacturing is the highest of all verticals from an IoT technology investment perspective. It's also thanks to IoT that digital twins become affordable and most certainly alter the face of manufacturing technology. [6]

PREDICTIVE MAINTENANCE – INCREASING UPTIME AND REDUCING RISKS

Predictive maintenance always seemed like the perfect use case for the Internet of Things (IoT), more specifically for Industrial IoT (IIoT) and environments where uptime of specific assets is critical and breakdowns can have important consequences for several reasons. Many of the main technologies that are mentioned in the context of the Industry 4.0 play a role in predictive maintenance (Maintenance 4.0, PdM 4.0) and its evolutions: big data, artificial intelligence, machine learning, IoT, cloud computing, data analytics and, increasingly, edge computing and digital twins.

Sensors and actuators are transducers (Figure6). A transducer converts a specific signal which comes in a specific form of energy into another signal in a different form of energy. Sensors convert signals in areas such as heat, humidity, pressure, presence of gases, pressure, acceleration and so forth into a digital signal that gets sent to a control and/or data aggregation systems such as a sensor hub or gateway. They are the start of all IoT data capture and thus must be accurate. The exact types of sensors (there are over a hundred) depend on what should be achieved. In some IoT use cases, projects or devices there are only a few sensors (per connected device), in others there are often thousands.

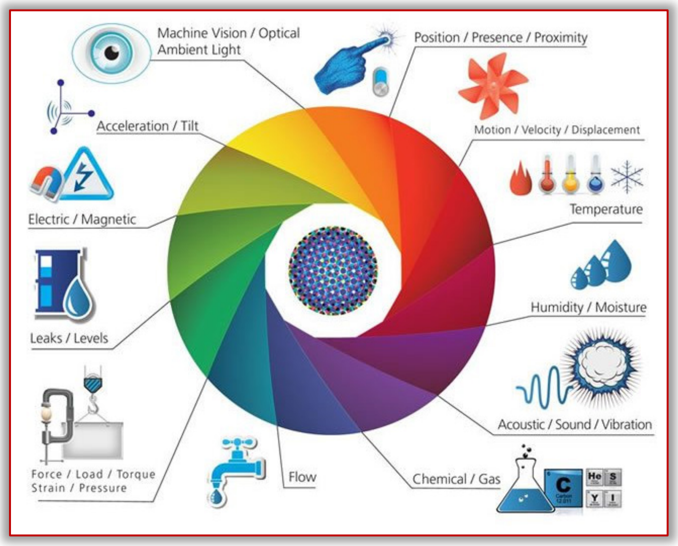

Figure 6. IoT devices – sensors and actuators examples [19]

Transmission systems of vehicles and tractors operate under conditions of varying speeds and loads. In addition to internal factors, external ones (the road surface, car loading, driver skills) influence on the vibration characteristics of transmission units. The main feature of the developed diagnostic method is using conceptual modelling for the oscillating process in the gear drive and the propagation of vibrations in the transmission. It is advisable to apply together integral diagnostic models and predictive ones based on damage accumulation. Such a 'two–coordinate' approach (two points of view) ensures higher veracity of the individual lifetime forecast. [2]

An example is a reducer of a motor wheel of a mining dump truck. The reducer of a motor wheel with installed sensors is shown in Figure 7, and processes in an onboard monitoring system are in Figure 8.

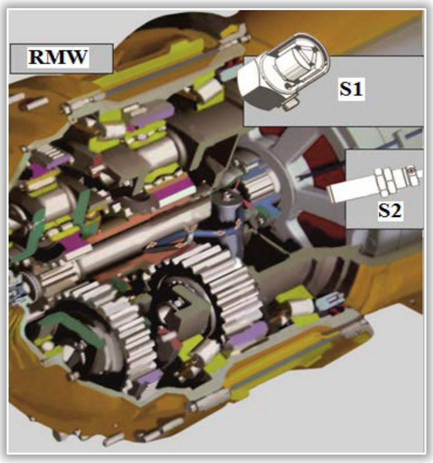

Figure 7. Reducer of a motor wheel with sensors [2]

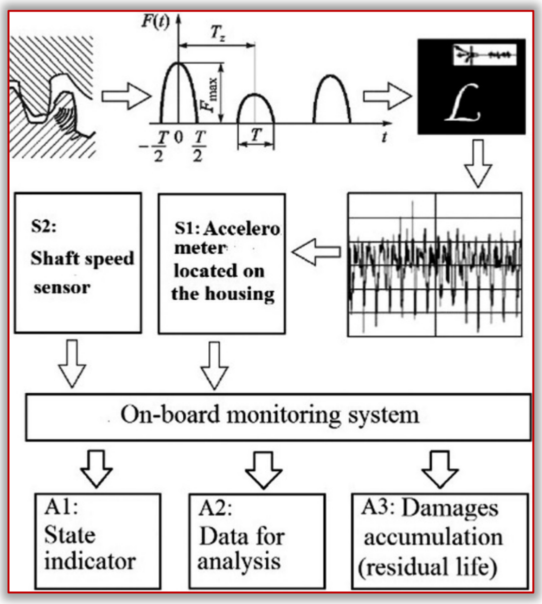

Figure 8. Processes in the RMW and its monitoring system [2]

Industrial IoT, in combination with predictive analytics and machine learning, however, are the main drivers of the more mature stage of predictive maintenance. Actionable, often real–time, data on pre–defined factors are gathered from smart sensors and predictive analytics algorithms are applied to predict when something might occur – and thus proactive maintenance, called predictive in this case, is needed.

The idea of predictive maintenance is simple and attractive enough and is similar to other forms of proactive maintenance with some additional benefits (and disadvantages): unexpected failure of equipment with all related consequences can be avoided, and maintenance can occur before something happens, instead of after the facts (reactive and run–to–failure maintenance), when such is deemed useful and possible. So, predictive maintenance is one of the maintenance methods enabling to do this kind of proactive maintenance and takes the most time and skills to implement. In other words: it's important to use it where it makes true sense.

Typical goal statements of PdM 4.0:

- maximize utilization, minimize costly downtime,
- replace close to failure components only,
- enable just in time estimating order dates,
- discover patterns for problems,
- key performance indicator of asset condition,
- reduce risk.

Predictive maintenance uses machine learning engines with these parameters of the monitored equipment being used as a basis, but the actual difference concerning what the machine learning and predictions say is what is likely to occur within a specific time frame and with a specific probability. Typically, this also means that predictive maintenance uses more data sources and sets than the sensor data from condition monitoring and digitally recorded data from the previous stage, instrument inspection. The difference might seem small, but it's not. Predictive maintenance uses monitoring data, but it uses more and, most importantly, it, indeed, predicts.

Almost all industries require effective tools or systems that help manage large data and use it to infer outcomes based on different situations. IoT technology comprises sensors and advanced gateway connectivity, which derive informed insights for the managers. It enables quick responses and better decision–making.

IoT promotes effective asset management strategies and enhances their performance by sharing valuable information with the managers. This helps reduce their workload of manually operating each task and rather automates the entire industrial processing. Hence, it leads to comparatively lower maintenance of the assets and simplifies the decision–making process. [19]

Keeping equipment in an operational state significantly reduces operating costs, saving the budget for manufacturers. Using sensors, cameras and data analytics, managers in several different product lines are now able to determine when a machine will break down before it stops. IoT–enabled systems can sense warning signs by using data that helps managers create maintenance deadlines and schedule equipment services before any problems occur.

Using real–time data from sensors and actuators, operations managers can quickly access current equipment conditions, recognize warning signs, receive alerts about problems, and get rid of wasting time into scheduling maintenance.

The sensor devices extract information from the assets and transfer the same through the gateway on the connected dashboard. This improves data storage on the cloud–based platform and processes it further in a user–friendly language, allowing effective productivity. The managers find this data easy to analyze and discuss the industrial flaws to encourage improvements in business strategies. [19]

DIRECTING THE DEVELOPMENT OF GEAR TRANSMISSIONS TO THE POSTULATES OF INDUSTRY 4.0

The function of driving systems is realized by the joint action of mechanics, sensors, actuators with appropriate information processing. Mechanics in this context should be understood as all components that directly participate in power transmission. Sensors and actuators also consist of mechanical components, but in this case, they represent the connection between the mechanics and the processor for processing information. With the help of sensors, it is possible to know the quantity of the actual values of individual operating parameters and transfer them to information processing systems. Information processing enables the successful control of power flow and work processes by comparing the actual and set values of the operating parameters of the system, and thus manages the system in order to fulfil its operating function.

Therefore, modern driving systems with these performances are in fact mechatronic systems, which in nowadays conditions of technical development are extremely important. The principle of driving systems operating is usually based on rotational or rotational–translational movement (transport mechanisms, industrial plants).

The power transmission system basically consists of three subsystems: driving engine, power transmission and operating machine. These subsystems consist of mechanical and structural elements. Gears, couplings, shafts, seals and bearings play the most important role in the synthesis of these subsystems.

These three subsystems form one oscillatory system, which is exposed to different influences, i.e. alternating loads. Vibrations negatively affect the successful execution of the system's operational function and can, in some cases lead to the appearance of a resonant state. Therefore, monitoring devices have to be installed in technical systems for monitoring the occurrence of vibrations and critical states of the components of the system.

There is a transmission of power and torque through the transmissions, so different forces occur on its components. In practice, various requirements are required from gear transmission. Thus, for example, in operating conditions, the direction of power flow can be changed, and thus the input and output of power are changed in transmission. There are often cases of branches aggregating or division of power. Particular structural elements often perform several different functions.

In practice, it happens that the constant gear ratio does not meet the working conditions, but it is necessary to bring power to several different places with different operating parameters. There are also cases where a change in both speed rotation and torque value in a wide range is required.

Progress in power electronics has made it possible to regulate speed electronically in some areas (for example a washing machine). Many mechanical couplings are replaced by the use of electronic controls, such as in production systems.

However, in many areas, power transmissions are irreplaceable, because they have many advantages: branching and summation of power, stepwise or continuous change of speed, reliable operation, energy efficiency and compactness of construction.

Driving systems are part of almost all types of machines and devices so the fulfilment of the work function in various areas of the industry depends on their reliable operation. If there is an aspiration to build smart factories, then the priority is the development and creation of smart driving systems. At the same time, it is a usual method not to change the design solution in the initial phase, but to install smart product systems in the existing solution of drive systems.

In this view, the following points should be considered:

- installation of sensors and software that enable full self–monitoring of the state of operating regularity of drive systems;
- installation of systems with integrated logic functions for monitoring the influential parameters of the operating machine and operating environment that affect the operation of drive systems;
- installation of a sensor module for data transmission and communication via IO–link, which as a result has a full connection with Industry 4.0.

For reliable operation of power transmission, it is very important to avoid critical conditions during operation. The risk of damage to the gearbox is reduced if the failures are detected at an early stage. Also, repair costs, as well as losses due to downtime, are avoided. For example, thermal stability and dynamic behaviour play a very important role in the reliable operation of the gear unit. It is the easiest to monitor them through temperature and vibration and to notice the exceeding of boundary conditions promptly through appropriate systems.

DIGITAL TRANSFORMATION OF UNIVERSAL HELICAL GEAR REDUCERS

The digitalization of helical gear reducers is transforming the business models and the manufacturing processes adopted by companies that operate in the industrial automation field. Such companies must meet requirements of more and more flexible production, in small batches, with high customization and short time–to–market, without giving up high technical performances and utmost quality levels. These gear reducer companies should make the effort of shaping a new automation era, more open, interconnected, intuitive and user–friendly. All this, thanks to the development of advanced products and technologies, concretely resulted in an innovative factory concept, called HUMANufacturing. This expression defines its way to Industry 4.0, where robots and the other industrial machines work in strict contact and in full safety with the operator, who remains central in the manufacturing process. [20]

Industry 4.0 has determined the need for a complete rethinking of production models that, from a "make to stock" logic, are evolving towards an "assembly to order" approach. Besides collaborative robots and other innovative products for industrial automation manufacturers have to develop solutions enabling the communication between operators and automation systems through mobile devices, developed according to the Industrial IoT vision. They are completed by preventive and predictive maintenance instruments. Such technologies are inspired by a right–sized automation strategy, aimed at an efficient balancing between machine use and human contribution in the productive context.

INNOVATIVE UNIVERSAL HELICAL GEAR REDUCERS – SENSORS INSTALLATION

In order to be adopted for smart factories, universal helical gear reducer should be expected installation of following sensors:

- Temperature sensor, which will monitor the oil temperature in the gearbox housing and if it reaches a boundary limit value then the sensor will "inform" the main processor. The system will assess whether the temperature rise is due to rising ambient temperature, in which the reducer is located, or due to a higher load of the reducer, which occurred due to a change in the technological process. The system will correct the operation of other components in the system and, if necessary, inform the operator, and in case of reaching a critical value, the processor will shut down the driving and, if necessary, the entire system in which it is installed.
- Oil level sensor, which will monitor the oil level in the gearbox housing. In case of reaching a certain minimum value, the sensor signal will inform the system to add oil, or in complex and responsible systems, register the place of oil loss, and even performed automatic refuelling, and informed the system. In case of reaching a critical oil level value and loss of a large quantity of oil, the sensor would turn off the drive and also inform the system.
- Vibration sensor, which will monitor the vibration level of the gearbox. If the vibration reaches the limit value, the processor would check the condition of other components in the system and check whether the cause of increased vibration is some external sources (some irregularity in the technological process) or an announcement of the forthcoming failure of some gearbox component. In the case the critical vibration value is reached, the sensor would timely prepare the shutdown system and turn off the gearbox and the entire system, if necessary. By applying special systems for vibration spectrum analysis, it would be possible to determine the cause of higher vibrations (bearing damage, gear damage, shaft bending, etc.) in responsible systems, which would speed up the elimination of the causes of elevated vibrations, or, if necessary, timely indicate for the implementation of appropriate activities.
- Rotation sensor, which will monitor the rotation number of the output shaft (or gear). For example, in case the engine is running, and the output shaft does not rotate, the sensor would turn off the drive and immediately notify the system. Of course, this sensor would monitor the actual number of revolutions and in case of a significant change, through the appropriate processor, would conclude the need for a change in the transmission process, or would adjust the number of revolutions to adapt to new ones.
- The operating time sensor, which will monitor the operating time between two oil changes. When it passes the estimated time for replacement, it will notify the system.
- Total operating time sensor, which monitors the total operating time of the gearbox, in order to indicate the performing the service, i.e. mandatory repairing the gearbox or to indicate the period of occurrence of possible gearbox failures.

In the future, motor gearboxes, i.e. their electric motors, will certainly be, even more often than before, equipped with drive control devices (usually frequency regulators) which would automatically adjust the speed of the gearbox output shaft to the requirements of the technological process under full load. Electric motors will be supplied with processors that provide the so–called soft start so that there are no sudden impacts during the start that significantly shorten the service life of the gearbox.

Figure 9. Innovative solution of universal single–stage helical gearbox: (1) solution of company REGAL [21], (2) solution of company STM TEAM [22], solution of company PGR [23]

Despite the fact that the current solutions of universal gear reducers have very good design solutions, their appearance will have to be paid even more attention because all other parameters (quality, price, delivery times, etc.) for most gear manufacturers, will be similar. [24] Therefore, the appearance solution of gears will greatly affect their placement. For example, today the solutions of single–stage motor gearboxes of the company REGAL (Figure9–1) are especially interesting. The design of single–stage gearboxes of companies STM TEAM (Figure9–2) and PGR (Figure9–3) are also interesting. Similar solutions can be expected from other gearbox manufacturers in the future.

Interesting design solutions for two–stage helical gear reducers are solutions of company SESAME (Figure10–1), Stöber (Figure10–2) and BEGE (Figure10–3).

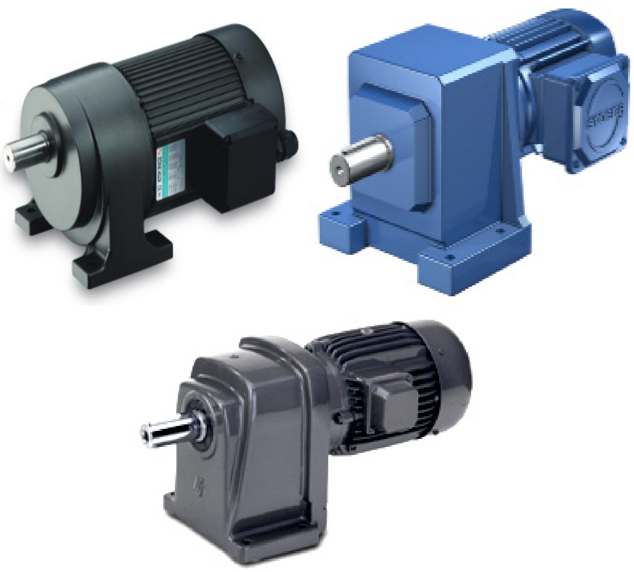

Figure10. Innovative solution of universal two–stage helical gearbox: (1) solution of company SESAME [25], (2) solution of company Stöber [26], (3) solution of company BEGE [27]

Interesting design solutions for three–stage helical gear reducers are solutions of the company Siemens (Figure11–1), Motive (Figure11–2) and Rossi (Figure11–3). Also, there are innovative solutions in other types of gear reducer mounting, for example, shaft–mounted gearbox with axial mounting, but also in other types of gear transmission (bevel, worm, harmonic, etc.).

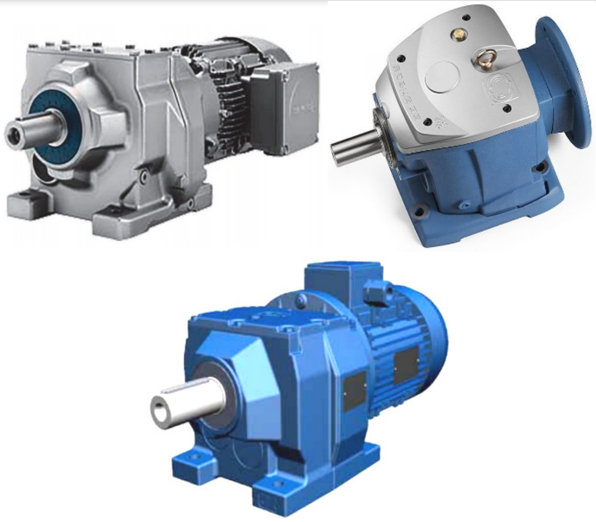

Figure11. Innovative solution of universal three–stage helical gearbox: (1) solution of company SIEMENS [28], (2) solution of company Motive [29], solution of company (3) ROSSI [30]

CONCLUSIONS

The goal of Industry 4.0 is to enable autonomous decision–making processes, monitor assets and processes in real–time, and enable equally real–time connected value creation networks through early involvement of stakeholders, and vertical and horizontal integration.

Industry 4.0 represents the digital transformation of manufacturing. It's most important benefits and potential perspectives are enhancing productivity, automation and the optimization of operational processes, business processes, and manufacturing operations, followed by (predictive) maintenance and smart maintenance services. In order to move to intelligent manufacturing, smart factories, or connected industries, it should bridge things such as real things, people, standards, work processes (man and machine) and more. Moreover, to bridge all that need data and networks. They must all inter–operate and inter–connect. It should bridge IT and OT, have assets such as machines that can connect and communicate thanks to sensors and other equipment and connect people, data, and machines. This is indeed mainly about the Internet of Things and, in a broader perspective the Internet of Services, Internet of People, Services and Things and Internet of Everything.

The digital twin may drive tangible value for companies, create new revenue streams, and help them answer key strategic questions. With new technology capabilities, flexibility, agility, and lower cost, companies may be able to start their journeys to create a digital twin with lower capital investment and shorter time to value than ever before. A digital twin has many applications across the life cycle of a product and may answer questions in real–time that couldn't be answered before, providing kinds of value considered nearly inconceivable just a few years ago. Perhaps the question is not whether one should get started, but where one should start to get the biggest value in the shortest amount of time, and how one can stay ahead of the competition. What will be the first step, and how will it get started? It can be an overwhelming task to get there, but the journey starts with a single step. [10]

The beginning of the period of Industry 4.0 was conditioned by using communication between cyber–physical systems and the internet of things (IoT) and all other parts of the production process. Having all that in mind, it can be concluded that further development of gear transmissions will be aimed at the greater application of artificial intelligence and machine learning, primarily various sensors and processors that will monitor and regulate their work and communication with other segments within the same technological process. These smart gearboxes will have a nice appearance design and high–class technical characteristics, with applied product personalization and customization and a short delivery time.

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