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INSTITUTE OF AUTOMATION AND COMPUTER SCIENCE

ÚSTAV AUTOMATIZACE A INFORMATIKY

DESIGN OF AN ADVANCED ROBOTIC CELL IN THE CONTEXT OF INDUSTRY 4.0

NÁVRH POKROČILÉ ROBOTICKÉ BUŇKY V KONTEXTU PRŮMYSLU 4.0

DOCTORAL THESIS

DIZERTAČNÍ PRÁCE

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Declaration of Authorship

I declare that I have written my doctoral thesis on the theme of "Design of Advanced Methods in the Field of Industrial Robotics, Fitting into the Concept of Industry 4.0" independently, under the guidance of the doctoral thesis supervisor, and using the technical literature and other sources of information, which are all quoted in the thesis and detailed in the list of literature at the end of the thesis.

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February 29, 2024

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Date	Ing. Roman Parák

Preface

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CHAPTER 1

Introduction

"An automated machine that does just one thing is not a robot. It is simply automation. A robot should have the capability of handling a range of jobs at a factory."

— Joseph Engelberger (1925 - 2015), *"The Father of Robotics"*

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CHAPTER 2

Current State in the Field of Industry 4.0

The following chapter introduces the state-of-the-art in Industry 4.0, the basic vision of which was first presented in 2011 by Professor Wolfgang Wahlster at the Hannover Messe trade fair in Germany [1]. A detailed concept of the Fourth Industrial Revolution was later presented at the same fair in 2013 [2].

2.1 History of the Industrial Revolution

In this section, we briefly discuss the history of the rise of the Fourth Industrial Revolution (usually called Industry 4.0), which began in the late 18th century and continues to the present day [3]. The historical process of industrial modernization, from the First to the Third Industrial Revolution, is thoroughly depicted in the book "The Industrial Revolution in World History" [4], and a brief review of these three revolutions can be found in [5, 6, 7]. The Fourth Industrial Revolution is discussed in the book "The Fourth Industrial Revolution" [8], but as a still relatively new area of research, it is more widely described in scientific publications (see [9, 10, 11, 12, 13]).

The historical process of the sequence of industrial revolutions with key pillars is depicted in Figure 2.1.

The First Industrial Revolution

The first phase of the Industrial Revolution began at the end of the 18th century, more precisely in 1760, and lasted until 1880.

The major milestones of the first industrial revolution include the invention of the steam engine and the development of steam power, as well as the use of turbine engines and water as power sources. The steam engine enabled the transition from agriculture to

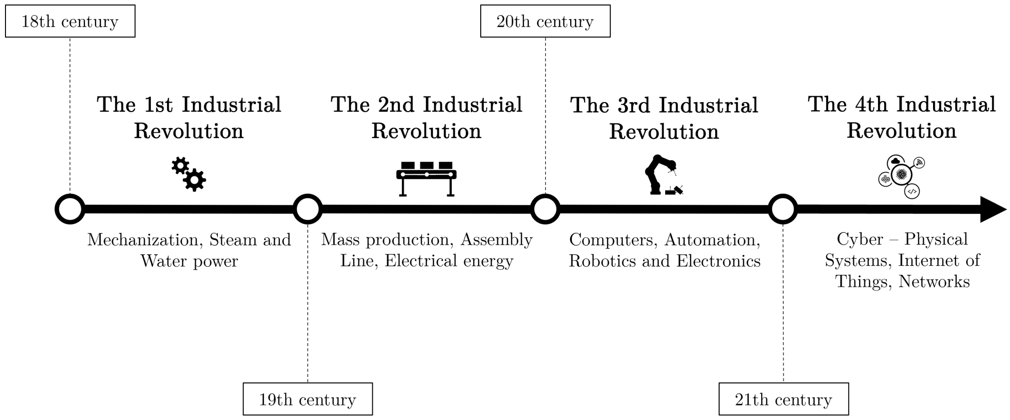

Figure 2.1: A visualization of the historical process of industrial revolutions that began in the 18th century and continues to the present day.

a new production process. This transition involved the use of coal as the main source of energy.

The combination of steam power and mechanized production caused a significant change in performance, not only in terms of the growth of the regional and global market economy but also in education, where the science and technology sector was inspired to restructure academic fields.

The Second Industrial Revolution

The second phase of the Industrial Revolution began in 1880 and lasted until 1950.

One of the major milestones of the first industrial revolution was the invention of the internal combustion engine. This invention facilitated technological advances in the industry, leading to rapid industrialization through the utilization of oil and electricity for mass production and assembly lines. A wave of systemic change has led to the belief that science and technology are the ways to a better life, and that progress is, in many ways, necessary. The revolution has brought fundamental changes in standardization and precision manufacturing, as well as large-scale technological infrastructure, such as electricity grids and new forms of public transport based on the internal combustion engine.

In addition to innovations such as the steamship, the telephone, and the gas turbine, the public developed a desire for goods, travel, and, not least, information, which were major factors in future development.

The Third Industrial Revolution

The third phase of the Industrial Revolution began in 1950 and lasted until 2010.

A characteristic feature of the Third Industrial Revolution was the implementation of electronics and information technology to automate production. With the advent of computers, infrastructure was established, resulting in a significant shift in information theory and the potency of data. Last but not least, new channels were created for sharing information. In many ways, the rapid advancement towards enhanced computing power has led to a more interconnected and complex problems that need to be addressed.

Innovations, such as programmable logic controllers and single/multi-purpose robotic systems, as well as the advancement of nuclear power, have opened the door to new areas of research, including space, robotics, and biotechnology.

The Fourth Industrial Revolution

The fourth phase, also called Industry 4.0, was first introduced in 2011 by Professor Wolfgang Wahlster at the Hannover Messe trade fair in Germany [1] and continues to the present day.

A characteristic feature of Industry 4.0 is the transformation of industrial production through the integration of digital and internet technologies, the utilization of cyber-physical systems, artificial intelligence techniques, augmented reality, physical simulation, additive technologies, and other key aspects to achieve the greatest possible flexibility in the production process.

A more detailed description of Industry 4.0, including the characteristics of the industrial concept and a brief introduction to the main pillars, is described in Section 2.2.

2.2 The Characteristics of the Fourth Industrial Revolution

As the title implies, the following section introduces the characteristics of the Fourth Industrial Revolution.

The main idea of the Industry 4.0 concept involves the integration of intelligent machines and systems into the manufacturing processes of industrial enterprises [14, 15]. The concept of the Fourth Industrial Revolution is based on the nine main pillars (see Fig. 2.2) [16, 17, 18], which together form the core idea of the digitization of industry. The aim of the concept is to increase work efficiency and personalization, which leads to flexibility in changes to the production of a designated range of products. The Fourth Industrial Revolution focuses not only on changes in technology development but also on the way people work and the utilization of their creativity in various industries. By increasing the level of information processing and evaluation through the integration of AI techniques, the concept achieves improvements in various areas such as security, human-machine collaboration [19], predictive maintenance, visual inspection, etc. In addition to the industrial sector, where the Industry 4.0 initiative is an integral part, it also affects the development of education [20, 21], transportation, agriculture, and many other fields.

Industry 4.0 encompasses six design principles in its characteristics [22, 23, 24], namely modularity, interoperability, etc. These principles are referred to as "design principles" because they contribute to the design or transition process from Industry 3.0 to Industry 4.0.

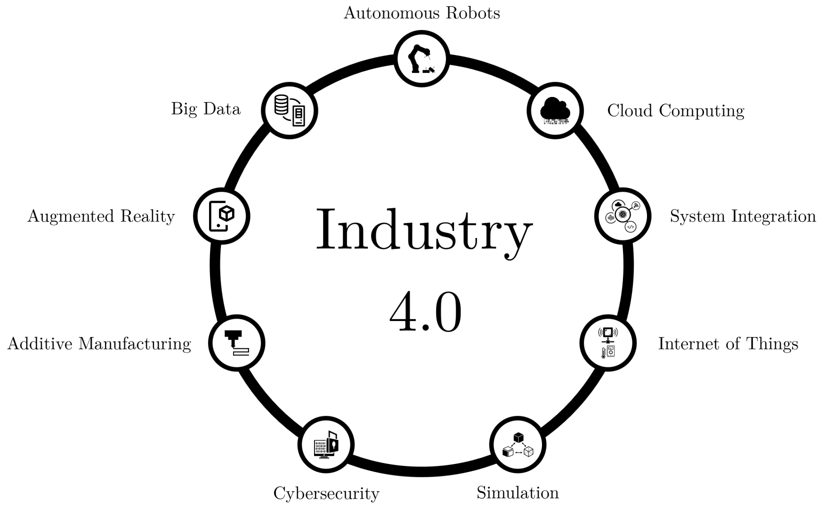

Figure 2.2: The nine main pillars of the concept of the Fourth Industrial Revolution.

The main design principles of Industry 4.0

(a) Modularity

The principle of modularity refers to customization and adaptation to different requirements. This principle offers scalability, flexibility, and the ability to upgrade or replace specific components without affecting the entire system.

(b) Interoperability

The principle of interoperability refers to the fact that a cyber-physical system (CPS) comprises intelligent machines and intelligent storage systems and facilities capable of autonomously exchanging information, initiating actions, and controlling each other independently. This involves standardizing communication protocols and data formats to ensure compatibility among different components and technologies.

(c) Decentralization

The principle of decentralization refers to the fact that different components and machines can make autonomous decisions based on real-time data, reducing the need for a central controller. Tasks are delegated to a higher level only in cases of failure.

(d) Real-time capability

The principle of real-time capability refers to the ability of systems, manufacturing processes, and intelligent machines to operate and respond to events in real-time or near-real-time.

(e) Virtualization

The principle of virtualization refers to the creation of virtual representations or simulations of physical entities, processes, or systems within the industrial environment. The sensor data are linked to virtual plant models and simulation models. Thus, a virtual copy of the physical world can be created.

(f) Service orientation

The principle of service orientation emphasizes the organization and delivery of functionality as services, marking a shift from merely selling products to offering integrated products and services that provide more value to the customer. This involves the use of SOA architecture (Service-Oriented Architectures).

2.3 The main pillars of Industry 4.0

In this section, we briefly introduce the main pillars of the Fourth Industrial Revolution, as illustrated in Figure 2.2 from the previous section. Since some key pillars, such as system integration, autonomous robots, and simulation, are more crucial than others for the practical implementation of the presented thesis, we will pay more attention to them.

As we can see in [14, 15, 18, 25], the key pillars of Industry 4.0 do not include AI techniques such as machine learning, deep learning, etc. AI technologies are still a relatively new field in practical applications that have not been sufficiently tested to be incorporated into the pillars that form the Fourth Industrial Revolution. On the other hand, machine learning, deep learning, and other AI techniques can be found as important components in most of the key areas mentioned above.

2.3.1 System Integration

In the Industry 4.0 landscape, systems integration plays a crucial role in transforming manufacturing processes into interconnected, intelligent, and efficient systems. System integration helps incorporate various technologies within the manufacturing process, including the Internet of Things (IoT), artificial intelligence techniques, cloud computing, robotics, single / multiple purpose machines, and cyber-physical systems. It ensures interoperability and real-time communication between different elements within an intelligent manufacturing environment.

There are three dimensions of system integration within Industry 4.0 [25]: vertical integration, horizontal integration, and end-to-end integration.

(a) Vertical Integration

Vertical integration involves the seamless interconnection and collaboration between different levels of the production process hierarchy. The concept of vertical integration refers to the interconnectedness of the entire industrial enterprise, i.e., all logical levels within the organization, from the production floor to the research department, product management, quality assurance, sales department, and so on. This type of integration refers to flexible and reconfigurable systems within the factory and the extent to which they are fully integrated with each other.

(b) Horizontal Integration

Horizontal integration involves the sharing of data outside the organization, i.e., from suppliers through manufacturers to distribution, to the end customer, and subsequent service. This type of integration facilitates the exchange of information and resources between different entities within a specific phase of the production process.

(c) End-to-End Integration

The goal of end-to-end integration is to create a seamless and interconnected flow of information and processes along the entire value chain, from the initial design phase to the delivery of the final product to the customer. This type of integration applies to all engineering processes throughout the product lifecycle.

Considering the fact that vertical system integration plays a role in supporting seamless interoperability and optimal interconnection between different components within Industry 4.0, which is an integral part of the presented thesis, we will briefly describe the most commonly used Ethernet-based communication protocols.

Ethernet POWERLINK

EtherNet/IP (EtherNet/Industrial Protocol) [26] is one of the most widely used standards that provides users with the tools to deploy standard Ethernet technology (IEEE 802.3 combined with the TCP/IP Suite) in industrial automation applications. The industrial protocol was developed as a result of the collaborative efforts of organizations such as ODVA (Open DeviceNet Vendor Association), ControlNet International, and Rockwell Automation.

EtherNet/IP is a fully compatible industrial protocol according to the IEEE 802.3 standard, utilizing a standard communication model with a solution at the application layer. Compliance with IEEE Ethernet standards provides a network interface with speeds ranging from 10 Megabits per second (Mbps) to 1 Gigabit per second (Gbps), which can be adjusted to meet user requirements. Additionally, it offers a flexible network architecture that is compatible with commercially available Ethernet installations. Within the EtherNet/IP network, individual nodes are assigned device types with specific characteristics and functions. The assigned device types and the communication network's application layer are created by the Common Industrial Protocol (CIP), which is used in industrial communications such as DeviceNet and ControlNet, employing a producer-consumer communication principle. The use of the CIP protocol achieves interoperability among all networks that support this protocol.

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PROFINET

PROFINET (Process Field Network) [27, 28] is one of the most widely used industrial communication protocols that plays a crucial role in real-time communication and data exchange in control systems. The industrial protocol was developed and standardized by PROFIBUS & PROFINET International (PI), designed to meet the demanding requirements of modern industrial environments. The PROFINET communication standard can be used to control manufacturing with various elements of industrial automation, such as linking the production process control to collect data from individual sensors capable of processing information at 100 Mb/s, based on ISO/IEC 8802.3.

PROFINET can be divided into the so-called Profinet CBA (Component Based Automation), which is used for modular systems such as Programmable Logic Controllers (PLCs), sensors, etc., and Profinet IO, which is used for distributed field devices. Both Profinet IO and Profinet CBA systems can operate simultaneously on the same network and can be implemented in the same communication station. The industrial PROFINET network can communicate in real-time (RT) at a speed defined by the cycle time.

OPC UA

OPC UA (Open Platform Communications Unified Architecture) [29] is an international standard for secure, reliable, and platform-independent industrial communication in the context of the Fourth Industrial Revolution. It provides a solid foundation for modern industrial automation and control systems. The OPC UA industrial standard was published in 2008 and standardized by the OPC Foundation [30] with the IEC 62541 norm.

The international standard is designed for seamless vertical integration in automation systems and allows any combination of client/server components at different levels of the automation hierarchy for a specific application. In addition, it utilizes object-oriented techniques to model the information, which is represented in a so-called OPC UA address space.

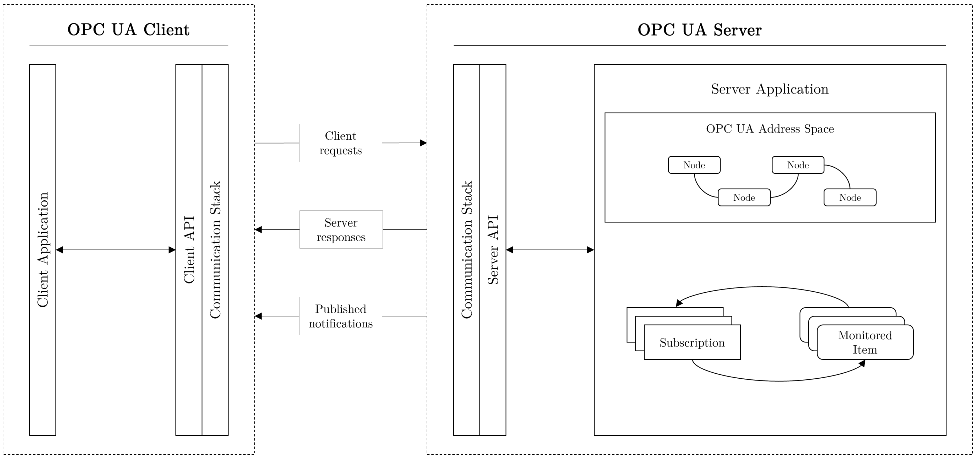

Figure 2.3: Typical client/server architecture of the OPC UA international standard [30].

2.3.2 Simulation

Simulation, specifically simulation tools, can be used in production processes to leverage real-time data and imitate the behavior of the physical world in a virtual model, known as the digital twin. The virtual model can include machines, sensors, products, and even people, resulting in increased productivity and quality of production. Using simulation tools, it is possible to optimize machine settings in a virtual environment before implementing them in the physical world. Simulations can be created for both 2D and 3D spaces, allowing us to optimize the production process, improve product quality, and, most importantly, prevent collisions and unexpected situations. The use of advanced simulation, which includes a physical representation of individual parts within the production process, can not only increase the efficiency, safety, and quality of production, but also prevent production failures.

Digital Twin

The term "digital twin" has evolved over the years, but with the emergence of the Fourth Industrial Revolution, it has become more generalized. In the context of Industry 4.0, a digital twin is a virtual representation of a physical object, system, or process. The virtual model is created through the integration of real-time data from sensors, devices, and other sources connected to the physical entity. The digital twin mimics the physical object in terms of its structure, behavior, and performance, and enables simulation, analysis, and monitoring throughout the entire lifecycle, i.e. from design and manufacturing to operation and maintenance.

According to [31, 32], digital twins can be divided into three subcategories (shown in Figure 2.4) based on the level of data integration. In the following text, all the major subcategories are briefly described: the digital model, the digital shadow, and the digital twin.

(a) Digital Model

A digital model is a representation of a physical object in digital form without automated data flow between the physical and digital objects. In other words, a change in the state of the physical object does not directly affect the digital object and vice versa.

(b) Digital Shadow

A digital shadow is a digital representation of an object with a unidirectional data flow between the physical and digital objects. In other words, a change of state in the real world is reflected in the virtual world, but not vice versa.

(c) Digital Twin

A digital twin is a fully integrated representation of a physical object in both directions, i.e. the data flow between the physical object and the digital object is bidirectional. A change in the state of the physical object leads directly to a change in the state of the digital object, and vice versa.

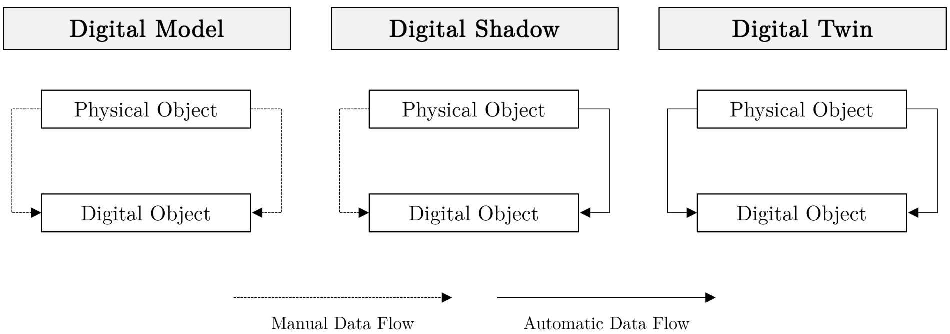

Figure 2.4: Three subcategories based on the data integration level of the digital twin model.

An article by Deloitte [33] provides a conceptual architecture that explains how the digital twin works in general (see Figure 2.5). It consists of five enabling components, including sensors, data, integration, analytics, and actuators, and a six-step process that includes creating, communicating, aggregating, analyzing, gaining insights, and taking action. Sensors and actuators are located in a physical space, while data analysis takes place in a virtual space. Integration technologies must be used to enable seamless data communication between the physical and virtual worlds. The conceptual architecture consists of a sequence of six operational steps based on digital twins: Create, Communicate, Aggregate, Analyze, Insight, and Act. More information about the conceptual architecture can be found in [34] and [35].

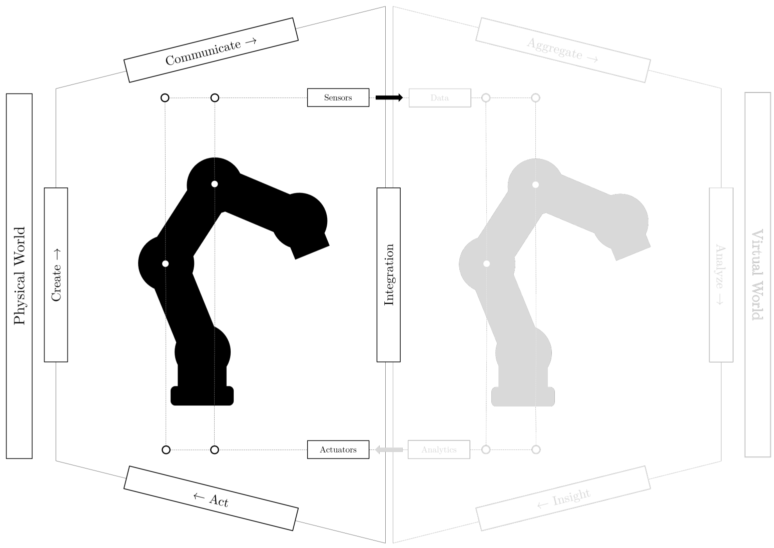

Figure 2.5: A conceptual architecture, consisting of five basic components and a six-step process, illustrates the general functioning of a digital twin.

2.3.3 Autonomous Robots

In the context of Industry 4.0, autonomous robotics is a key component. It is mainly used in the industry to address complex and dangerous tasks that are not suitable for humans. Additionally, autonomous robotics is used to replace stereotypical tasks traditionally performed by humans, thereby preventing the under-utilization of human potential. The use of robots in industrial enterprises is growing exponentially [36], as they significantly increase productivity, efficiency, repeatability, and human safety. Robots as autonomous systems can be used in various industries, such as manufacturing, agriculture, healthcare, etc., to perform a variety of tasks, including intelligent sorting, safe interaction, and visual inspection.

A more detailed description of the principles of autonomous robotics, including the methods used for motion planning and control, is discussed in Section 4.

2.3.4 Other Pillars

In addition to the technological pillars already described, there are other key aspects of the Fourth Industrial Revolution that are necessary to maintain the basic concept.

Cloud Computing

Cloud computing is one of the crucial components of Industry 4.0 because it allows industrial enterprises to manage and visualize data in real-time with minimal interaction with service providers. The constraints on individual companies are minimized as the industrial revolution fosters increased data sharing between workplaces, driven by the imperative to optimize production. Cloud computing facilitates user mobility, resource conservation, and distributed data analytics to address various network-related issues. It also supports decentralization and intelligent processing of data generated by various Internet of Things (IoT) devices that integrate the physical world into cyberspace.

There are three main cloud service models [18, 37]: Infrastructure as a Service (IaaS), Platform as a Service (PaaS), and Software as a Service (SaaS).

(a) Infrastructure as a Service (IaaS)

The IaaS cloud service model provides virtualized computing resources over the internet, including virtual machines, storage, and networking.

(b) Platform as a Service (PaaS)

The PaaS cloud service model offers a platform that includes not only the underlying infrastructure, but also the development tools and services needed to build, deploy, and manage applications.

(c) Software as a Service (SaaS)

The SaaS cloud service model provides software applications over the internet on a subscription basis. Users can access these applications through a web browser.

Internet of Things

The Internet of Things (IoT), specifically the Industrial IoT, deals with the industrial communication of interconnected and uniformly addressed objects (i.e., industrial devices) that communicate via standard protocols. In general, the IoT can provide advanced interconnection of systems, services, physical objects, as well as enable communication between industrial devices and the sharing of large amounts of data. By implementing IoT in industrial enterprises, the company can achieve greater integrability, agility, and competitive advantages.

The Internet of Things (IoT) consists of the Internet of Services (IoS), the Internet of Manufacturing Services (IoMs), the Internet of People (IoP), embedded systems, and the Integration of Information and Communication Technology (IICT) [25].

Cybersecurity

Cybersecurity is one of the most crucial components of Industry 4.0, and it can have a significant impact on the business environment due to various attacks. With the increasing connectivity and the use of standard communication protocols (see Subsection 2.3.1) that accompany the Fourth Industrial Revolution, the need to protect critical industrial systems and production lines from cybersecurity threats increases dramatically. The key aspect of cybersecurity is secure and reliable communication, along with sophisticated machine access management. Securely connecting both the physical and digital worlds can enhance the quality of information required for planning, optimization, and production.

Closely related to cybersecurity is the concept of the Cyber-Physical System (CPS), which plays a crucial role in Industry 4.0. CPS has been defined as a system in which the physical world is fully integrated with computing, communication, and control systems, collectively referred to as the digital world. The main characteristics of CPS are decentralization and automatic control of the production process. The interconnection of the physical world, the service world, and the digital world can improve the quality of information needed for the planning, optimization, and operation of production systems.

Additive Manufacturing

Additive manufacturing, also defined as 3D printing, is considered the process of manufacturing various parts from computer-created 3D models. It deals with the production of small series of customized products according to customer requirements, offering construction advantages such as complex and lightweight designs. By eliminating the demanding technological preparation of production, shortening the construction process, and utilizing prototypes instead of finished products, the time required to bring the product to market can be reduced. Accurate estimation of the amount of material and simulation of the production process result in the optimization of order management. Considering that the production process involves gradually adding material, it is possible to determine its consumption with relative precision.

Additive technologies enable the production of various types of structurally complex parts without the need to reconfigure the machine and also without the need for complex software modification. The production process using additive technologies can adapt the product to the specific needs of the customer.

Augmented Reality

Augmented reality is defined as an interactive technology that allows connecting the physical world with the virtual one, while the virtual world is used as a part of the real environment. This technology in industrial enterprises enables human-machine interaction, machine and equipment maintenance, visual product inspection, etc. In addition to navigation systems, a key aspect of augmented reality is spatial data, which enables the connection of various information to a specific location. By combining a computer-generated environment and physical objects, it could be used in many applications, as creativity knows no limits.

From a technical point of view, the augmented reality system must solve two spatial problems in real-time, which consist of the localization of the user and his spatial vision. Augmented reality uses a combination of sensors (gyroscope, accelerometer, etc.) and computationally intensive machine vision algorithms based on artificial intelligence techniques.

Big Data

The concept of big data applies to large, diverse, and complex amounts of data that influence the organizational decision-making processes of industrial enterprises. According to Forrester's definition [38], Big Data consists of four dimensions: (1) the amount of data, (2) the variety of data, (3) the speed of generation of new data and analysis, and (4) the value of data. The volume of data in the industry is growing exponentially, thereby increasing the potential amount of usable information. However, the ability to collect and comprehensively evaluate information is necessary for further development. Therefore, the increase in the level of data and improvements in technological capabilities accelerate the increase in productivity and innovation.

In the context of Industry 4.0, big data analytics is beneficial in several areas of an industrial enterprise. It aids in predictive maintenance, improving equipment service, optimizing production quality, and, last but not least, saving energy. The analysis of previously recorded data is employed to detect threats that have occurred in various production processes and to predict new problems that may arise, in order to prevent them.

2.4 Testbeds for Industry 4.0 in the Czech Republic and the Surrounding Countries

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2.5 Forecasting the Future Landscape of the Industry

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CHAPTER 3

Kinematics

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CHAPTER 4

Motion Planning and Control

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CHAPTER 5

Robotic Cell in the Context of Industry 4.0

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CHAPTER 6

Conclusion

"If you want to improve something, you must first understand it. The combination of theoretical and practical knowledge is not an option, it is a must."

— Roman Parak

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Bibliography

[1] H. Kagermann, W. Wahlster, and J. Helbig, *Recommendations For Implementing The Strategic Initiative Industrie 4.0: Final Report of the Industrie 4.0 Working Group.* Ulrike Findeklee: Acatech – National Academy of Science and Engineering, 2013.

[2] H. Kagermann, W.-D. Lukas, and W. Wahlster, "Industrie 4.0: Mit dem internet der dinge auf dem weg zur 4. industriellen revolution," *VDI nachrichten*, vol. 13, 2011.

[3] A. Sharma and B. J. Singh, "Evolution of industrial revolutions: A review," *International Journal of Innovative Technology and Exploring Engineering*, vol. 9, no. 11, pp. 66–73, 2020.

[4] P. N. Stearns, *The industrial revolution in world history.* Routledge, 2020.

[5] H. Mohajan, "The first industrial revolution: Creation of a new global human era," 2019.

[6] H. Mohajan, "The second industrial revolution has brought modern social and economic developments," 2019.

[7] J. Mokyr and R. H. Strotz, "The second industrial revolution, 1870-1914," *Storia dell'economia Mondiale*, vol. 21945, no. 1, 1998.

[8] K. Schwab, *The fourth industrial revolution.* Currency, 2017.

[9] M. Xu, J. M. David, S. H. Kim, *et al.*, "The fourth industrial revolution: Opportunities and challenges," *International journal of financial research*, vol. 9, no. 2, pp. 90–95, 2018.

[10] P. Thomas and D. Nicholas, "The fourth industrial revolution: Shaping new era," *Journal of International Affairs*, vol. 72, no. 1, pp. 17–22, 2018.

[11] J. Rymarczyk *et al.*, "Technologies, opportunities and challenges of the industrial revolution 4.0: theoretical considerations," *Entrepreneurial business and economics review*, vol. 8, no. 1, pp. 185–198, 2020.

[12] C. O. Klingenberg, M. A. V. Borges, and J. A. do Vale Antunes Jr, "Industry 4.0: What makes it a revolution? a historical framework to understand the phenomenon," *Technology in Society*, vol. 70, p. 102009, 2022.

[13] A. Rojko, "Industry 4.0 concept: Background and overview.," *International journal of interactive mobile technologies*, vol. 11, no. 5, 2017.

[14] S. I. Tay, T. Lee, N. Hamid, and A. N. A. Ahmad, "An overview of industry 4.0: Definition, components, and government initiatives," *Journal of Advanced Research in Dynamical and Control Systems*, vol. 10, no. 14, pp. 1379–1387, 2018.

[15] M. Rüßmann, M. Lorenz, P. Gerbert, M. Waldner, J. Justus, P. Engel, and M. Harnisch, "Industry 4.0: The future of productivity and growth in manufacturing industries," *Boston consulting group*, vol. 9, no. 1, pp. 54–89, 2015.

[16] D. Palka and J. Ciukaj, "Prospects for development movement in the industry concept 4.0," *Multidisciplinary Aspects of Production Engineering*, vol. 2, pp. 315–326, 09 2019.

[17] Y. Uygun, "The fourth industrial revolution-industry 4.0," *Available at SSRN 3909340*, 2021.

[18] G. Erboz, "How to define industry 4.0: Main pillars of industry 4.0," *Managerial trends in the development of enterprises in globalization era*, vol. 761, pp. 761–767, 2017.

[19] F. Sherwani, M. M. Asad, and B. S. K. K. Ibrahim, "Collaborative robots and industrial revolution 4.0 (ir 4.0)," in *2020 International Conference on Emerging Trends in Smart Technologies (ICETST)*, pp. 1–5, IEEE, 2020.

[20] A. Oke and F. A. P. Fernandes, "Innovations in teaching and learning: Exploring the perceptions of the education sector on the 4th industrial revolution (4ir)," *Journal of Open Innovation: Technology, Market, and Complexity*, vol. 6, no. 2, p. 31, 2020.

[21] A. A. Shahroom and N. Hussin, "Industrial revolution 4.0 and education," *International Journal of Academic Research in Business and Social Sciences*, vol. 8, no. 9, pp. 314–319, 2018.

[22] M. Hermann, T. Pentek, and B. Otto, "Design principles for industrie 4.0 scenarios: A literature review," 01 2015.

[23] J. Ortiz, W. Marroquin, and L. Cifuentes, *Industry 4.0: Current Status and Future Trends.* 03 2020.

[24] R. Hall, S. Schumacher, and A. Bildstein, "Systematic analysis of industrie 4.0 design principles," *Procedia CIRP*, vol. 107, pp. 440–445, 2022. Leading manufacturing systems transformation – Proceedings of the 55th CIRP Conference on Manufacturing Systems 2022.

[25] S. Vaidya, P. Ambad, and S. Bhosle, "Industry 4.0 – a glimpse," *Procedia Manufacturing*, vol. 20, pp. 233–238, 2018. 2nd International Conference on Materials, Manufacturing and Design Engineering (iCMMD2017), 11-12 December 2017, MIT Aurangabad, Maharashtra, INDIA.

[26] P. Brooks, "Ethernet/ip-industrial protocol," in *ETFA 2001. 8th International Conference on Emerging Technologies and Factory Automation. Proceedings (Cat. No. 01TH8597)*, vol. 2, pp. 505–514, IEEE, 2001.

[27] J. Feld, "Profinet-scalable factory communication for all applications," in *IEEE International Workshop on Factory Communication Systems, 2004. Proceedings.*, pp. 33–38, IEEE, 2004.

[28] A. L. Dias, G. S. Sestito, A. C. Turcato, and D. Brandão, "Panorama, challenges and opportunities in profinet protocol research," in *2018 13th IEEE International Conference on Industry Applications (INDUSCON)*, pp. 186–193, IEEE, 2018.

[29] W. Mahnke, S.-H. Leitner, and M. Damm, *OPC unified architecture.* Springer Science & Business Media, 2009.

[30] OPC Foundation, "Opc unified architecture." `www.opcfoundation.org/`. Online. Accessed on 7 October 2023.

[31] W. Kritzinger, M. Karner, G. Traar, J. Henjes, and W. Sihn, "Digital twin in manufacturing: A categorical literature review and classification," *Ifac-PapersOnline*, vol. 51, no. 11, pp. 1016–1022, 2018.

[32] A. Fuller, Z. Fan, C. Day, and C. Barlow, "Digital twin: Enabling technologies, challenges and open research," *IEEE access*, vol. 8, pp. 108952–108971, 2020.

[33] A. Parrott and L. Warshaw, "Industry 4.0 and the digital twin," *Deloitte Insights*, 2017.

[34] F. Pires, A. Cachada, J. Barbosa, A. P. Moreira, and P. Leitão, "Digital twin in industry 4.0: Technologies, applications and challenges," in *2019 IEEE 17th International Conference on Industrial Informatics (INDIN)*, vol. 1, pp. 721–726, IEEE, 2019.

[35] T. R. Wanasinghe, L. Wroblewski, B. K. Petersen, R. G. Gosine, L. A. James, O. De Silva, G. K. Mann, and P. J. Warrian, "Digital twin for the oil and gas industry: Overview, research trends, opportunities, and challenges," *IEEE access*, vol. 8, pp. 104175–104197, 2020.

[36] C. Weidemann, N. Mandischer, F. Kerkom, B. Corves, M. Hüsing, T. Kraus, and C. Garus, "Literature review on recent trends and perspectives of collaborative robotics in work 4.0," *Robotics*, vol. 12, p. 84, 06 2023.

[37] K. C. Haug, T. Kretschmer, and T. Strobel, “Cloud adaptiveness within industry sectors–measurement and observations,” *Telecommunications policy*, vol. 40, no. 4, pp. 291–306, 2016.

[38] K. Witkowski, “Internet of things, big data, industry 4.0–innovative solutions in logistics and supply chains management,” *Procedia engineering*, vol. 182, pp. 763–769, 2017.

Appendix A: Activities within Doctoral Studies

Text ...

Appendix B: Source Codes

"Active participation within the open-source community, not only as a user but also as a contributor, is essential to ensuring continued growth."

— Roman Parak

Text ...