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Exploring Industrial Robotics And Its Impacts On Industrial Learning And Evolution

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Abstract
This article addresses the historical trajectory and technological evolution of industrial robotics, from the first automated mechanisms of Antiquity to the modern intelligent systems used in today's production lines. The survey highlights the importance of automation for the efficiency of production processes, as well as the social and economic impacts associated with its adoption. The generations of industrial robots, their main components and the role of human participation in the development and operation of these systems are discussed. Through a multidisciplinary methodological approach, the study highlights the growth of robotics in the industrial sector and proposes reflections on the challenges and opportunities imposed by automation. It is concluded that industrial robotics is a strategic tool for the advancement of manufacturing, as long as it is accompanied by policies of training and adaptation of the workforce.

Keywords: *Industrial robotics; Automation; Technological generations; Productive efficiency; Socioeconomic impacts; Industry 4.0.*

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I. Introduction

The history of industrial robotics is intrinsically linked to the evolution of tools and technology throughout the human trajectory. Since the dawn of civilization, human beings have sought to use instruments that help them in their daily activities, particularly in the fulfillment of basic survival needs. In the context of Western civilization, technological evolution has always been seen as a reflection of human development, where the improvement of tools and machines became a central objective, with the hope that these could replace man in his tasks, ensuring greater efficiency and productivity.

This search for automation goes back to ancient thoughts, such as those of Aristotle, who as early as the fourth century B.C. suggested the idea of machines that could perform their own tasks, anticipating human needs. Over the centuries, many inventions have boosted the ability to create increasingly complex machines, but it was with the Industrial Revolution that the real transformation took place, with the systematic application of scientific knowledge to industry. Francis Bacon, at the end of the sixteenth century, highlighted the importance of applying science in practice, transforming people's living and working conditions through technological advances.

With the invention of the steam engine by James Watt in 1769, the world began to experience a new cycle of development. Automation began to take shape, especially in industries, and production processes became faster and more efficient. At the beginning of the twentieth century, the figure of Henry Ford revolutionized mass production with the introduction of rigid automation, which allowed the serial manufacture of standardized products, promoting gains in productivity and quality.

In recent decades, however, industrial needs have changed, driving the creation of more flexible and adaptable systems. Programmable and flexible automation have emerged as a response to this new demand, allowing the manufacture of smaller and varied batches, meeting the customization of products without losing efficiency. In this scenario, industrial robots play a central role, as they are able to perform a variety of programmed movements, adapting to different operational needs. Its versatility is essential for the implementation of automation both in large-scale production processes and in more customized systems, being indispensable tools in the continuous evolution of industries.

This article explores the trajectory of industrial robotics, its impacts on the evolution of production processes and industrial learning, highlighting how these advances have transformed modern industry. Robotics not only improves efficiency and reduces costs, but also requires new forms of organization and training, shaping the way industries prepare for the challenges of the future.

II. Theoretical Reference

Industrial robotics has evolved over the last decades, transforming production processes and directly impacting the efficiency and flexibility of industries. Initially, industrial robots were limited to repetitive tasks in highly structured environments, being classified into different technological generations. The first generation, characterized by fixed-sequence robots, requires reprogramming to perform new tasks. The following generations, with the use of computational resources and sensors, enabled greater adaptation and decision-making capacity in more dynamic environments. Today, industrial robots are increasingly integrated into intelligent and flexible systems, expanding their applications and role in the modernization of factories.

Participation of a human operator

The degree of involvement of the human operator in the control process of a robotic system is determined by the complexity that the means of interaction presents and by the resources available for processing the data necessary for the execution of the tasks. In structured environments, where the parameters necessary for the system's operability can be identified and quantified, it is possible to establish a control system capable of managing and monitoring tasks with minimal operator participation. In this case, this system is classified as robotic.

Most automated activities related to industries, such as spot or continuous welding, attaching integrated circuits to boards, painting surfaces, moving objects, and assembling parts, operate in structured environments. In unstructured environments, due to the difficulty of quantifying certain process parameters or the high cost of obtaining them within certain specifications, the use of the operator's decision-making power in the management of the control system becomes fundamental for the accomplishment of the determined tasks. In this case, the system is classified as teleoperated. There are several applications in unstructured environments where a computer can process part of the information to be sent from the manipulated environment to the human operator and vice versa. Although this situation conceptually has a human operator in operational command, some degree of autonomy of the system is observed. Teleoperation-based systems are typically used in manipulations involving activities in unstructured environments such as mining, satellite recovery, handling of radioactive materials in nuclear power plants or research centers, and oil and gas exploration on offshore platforms.

Regarding technological generation

Another classification (RIVIN, 2021; ROSEN, 2022) refers to the technological generations of industrial robots. The first generation is that of robots called fixed sequence, which, once programmed, can repeat a sequence of operations and, to perform a different operation, must be reprogrammed. The robot's interaction environment in the factory must be completely structured (parameterized), as the operations require the precise positioning of the objects to be worked on. Most of the industrial robots in use belong to this generation.

Second-generation robots have computational resources and sensors that allow the robot to act in a partially structured environment, calculating in real time the control parameters for carrying out the movements. Some activities, such as picking up a part that is displaced from its ideal position and recognizing a part to be manipulated among a set of varied parts, are characteristics of this generation. The third generation of robots has enough intelligence to connect with other robots and machines, store programs, and communicate with other computer systems. It is able, for example, to make decisions in assembly operations, such as assembling a suitable combination of parts, rejecting defective parts, and selecting a correct combination of tolerances. The use of this type of robot in industrial processes is still incipient.

Definition of Robot

According to the Robotic Industries Association (RIA), an industrial robot is defined as a reprogrammable multifunctional manipulator designed to move materials, parts, tools, or special parts, through various programmed movements, to perform a variety of tasks (RIVIN, 2021). A more complete definition is presented by the ISO (International Organization for Standardization) 10218 standard, as being: "a manipulator machine with various degrees of freedom automatically controlled, reprogrammable, multifunctional, which can have a fixed or mobile base for use in industrial automation applications". An industrial robot is formed by the integration of the following components (RIVIN, 2021; SEERING, SCHEINMAN, 2022; WARNECKE et al., 2023; SCIESZKO, 2022; BORODIN, 2021).

a) Mechanical manipulator: refers mainly to the mechanical and structural aspect of the robot. It consists of the combination of rigid structural elements (bodies or links) connected to each other through joints (joints), the first body being called the base and the last terminal end, where the effecting component (claw or tool) will be linked.

- Links: It is inevitable that rigid links present some degree of flexibility when subjected to efforts during the performance of a task, whether static or dynamic in nature. Therefore, in robots, the structure must be designed to present high rigidity to bending and torsional forces. The most used materials in the structures are aluminum and steel. More recently, carbon and glass fibers, thermoplastic materials and reinforced plastics have been used.

- Joint: In robotics, two basic types of joints are generally used to compose a kinematic pair formed by two adjacent links: rotation joint or prismatic joint (translation). The use of these joints aims to simplify the process of assembling and/or manufacturing the mechanical components that make up a joint. Another advantage refers to the control of the relative movement between the links that depends on only one position variable. The number of degrees of freedom that a robot has is the number of position-independent variables that need to be specified in order to define the location of all parts of the mechanism, unambiguously. The industrial robot is typically a combination of links and joints in the form of an open powertrain. Therefore, the number of joints equals the number of degrees of freedom
- Transmission system: The movement of each body occurs due to the transmission of mechanical power (torque/force and angular/linear velocity) originating from an actuator. Transmission systems are mechanical components whose function is to transmit mechanical power from the actuators to the links. Among the most commonly used transmission components are gears (spur, helical, rack and pinion, bevel), recirculating ball screws, timing belts and pulleys, chains, cables, steel belts, planetary gears and harmonic gears. The choice of these components depends on design parameters such as the transmitted power, the types of movements desired, and the location of the actuator in relation to the controlled joint. The most important operating performance characteristics in drivetrains are rigidity and mechanical efficiency.

b) Actuators: These are components that convert electrical, hydraulic or pneumatic energy into mechanical power. Through the transmission systems, the mechanical power generated by the actuators is sent to the links so that they can move.

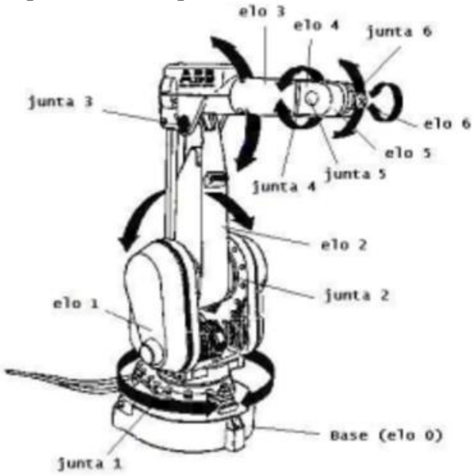
- Hydraulic and pneumatic actuators: Hydraulic and pneumatic actuators can take the form of linear cylinders to generate linear movements, or motors to provide angular displacements. Both are connected to directional valves (pre-actuators) that manage the direction of fluid displacement in the actuators, from signals generated from a control unit. The cost of high-performance directional valves still remains high. Hydraulic actuators allow the implementation of continuous and accurate control of positioning and speed due to the incompressibility of the fluid (hydraulic oil), resulting in high rigidity, but this can make force control unstable. Another characteristic is the high ratio between the mechanical power transmitted by the actuator and its weight, which makes it possible to build compact, high-power units. A pump is used to supply the hydraulic oil to the hydraulic actuator through the directional valves. Pneumatic actuators are used in industrial robots that operate with the movement of loads between well-defined positions limited by mechanical stops, which characterizes point-to-point movement. The low rigidity of these actuators due to the compressibility of the fluid (compressed air), allows smooth operations to be obtained, but this characteristic makes it not very precise as to the positioning control between the limit positions. The binary nature of the movement of these actuators (extended or retracted position) implies a simple and low-cost control. A compressor is used to supply the compressed air to the pneumatic actuator via directional valves. For the correct operation of the actuators, it is advisable to install preparation units (filter, drain, pressure regulator with pressure gauge, etc.) in the compressed air circuit before it enters the directional valves.
- Electromagnetic actuators: Electromagnetic actuators are the most commonly used in robots, especially direct current and stepper motor type actuators. As advantages, we can mention the wide variety of manufacturers available in the market, the fact that electric motors when associated with sensors can be used both to control the force and the position of the robot, and the ease of programming its movements, since these can be controlled by electrical signals, thus allowing the use of motion controllers.

Direct current (dc) type motors are compact and usually the torque value It remains in a constant range for large variations in speed, but it needs to angular position (encoder) and speed (tachometer) sensors for the control of Closed-loop positioning (servo control). The maximum mechanical efficiency of these Motors usually occur at high speeds, so the use of gearboxes is common to obtain the reduction of speed and consequently the increase of torque necessary for the transmission of mechanical power to the element moved. Currently the Robot manufacturers use brushless DC motors due to reduced maintenance, resulting from the reduction of wear and optimization of thermal dissipation between the rotor and the stator. Stepper motors can work in open-loop control in position and speed and are easily interconnected to low-cost control units, however, the torque curve decreases with increasing speed and at low speeds can generate mechanical vibrations. They are more used in the movement of claws. The AC motors, linear motors and solenoid type actuators have been more and more employed in mechanical manipulator projects. Recent research indicate that shape-memory materials have good potential to be used in the construction of actuators.

c) Sensors: They provide parameters on the behavior of the manipulator, generally in terms of the position and speed of the links as a function of time, and the mode of interaction between the robot and the operating environment (force, torque, vision system) to the control unit. The joints used to link the links of a robot are usually coupled to sensors.

d) Control Unit: Responsible for managing and monitoring the operational parameters required to perform the robot's tasks. The movement commands sent to the actuators originate from motion controllers (industrial computer, PLC, stepper controller board) and are based on information obtained through sensors.

Figure 1. Six-degree-of-freedom industrial robot



Source: Vitor Ferreira Romano and Max Suell Dutra, 2017

e) power unit: It is responsible for supplying the power necessary to move the actuators. The hydraulic pump, compressor, and electrical source are the power units associated with hydraulic, pneumatic, and electromagnetic actuators, respectively.
f) effector: It is the connecting element between the robot and the environment that surrounds it. It can be of the claw or tool type. The main purpose of a claw is to pick up a certain object, transport it to a pre-established position and after reaching that position, release it. The tool's function is to perform an action or work on a part, without necessarily manipulating it.

III. Methodology

The development of an industrial robot does not take place in isolation, but is an interdisciplinary process that involves the application of knowledge from different areas. The methodology proposed here follows a contextualized and projectual approach, considering the various stages and challenges that arise throughout the process of creating and implementing a robotic system.

Multidisciplinary Integration for Robot Development

The design of a robot requires intense collaboration between different areas of engineering. The mechanical engineering It is fundamental for the study of structures and mechanisms, addressing both the static and dynamic aspects necessary to ensure the robot's functionality. The Electrical and Electronic Engineering play a crucial role in the design and integration of the sensor, actuator and interface systems responsible for the connection between the robot and the environment. In turn, the Control Theory It is essential for the development of algorithms that enable the precise execution of movements, in addition to controlling the interaction between the robot and its work environment. The Computer Science completes the integration by providing the tools and languages needed to program robotic systems, making them capable of performing specific tasks in an efficient and adaptable manner.

Technical and Design Considerations for Robot Design

The interdisciplinary knowledge, the design of industrial robots involves a series of technical considerations. Or Actuator sizing, Mechanisms and Electronic circuits It is crucial to ensure that the robot has the strength, accuracy, and efficiency required for the proposed tasks. The Precision Parts Manufacturing & Assembly It requires strict control of tolerances and processes to ensure system functionality. The Material Selection Suitable for robot parts and components is equally important, aiming at the durability and strength required for the industrial environment. The Motion planning It must be carefully designed to optimize the robot's operational efficiency, considering its accuracy and speed. In addition, the Simulation and Modeling of the movements are performed to predict the robot's performance before implementation, allowing adjustments and improvements in the design.

Development of the Control and Programming System

The control system is one of the key elements of any industrial robot, being responsible for coordinating all its operations. To this end, the development of Programming Techniques It becomes essential, both for the control of the system and for the communication between the robot and the operator. The project must contemplate Operating Systems, capable of managing the interactions between the robot and the system components. It is also important to implement System Diagnostics and components, which makes it possible to identify failures and take corrective actions efficiently. The integration of these elements results in a functional robotic system, which performs tasks with the necessary precision and interacts efficiently with the environment.

Economic and Social Impact Analysis

Finally, the design of an industrial robot cannot be detached from its economic and social implications. The Cost-benefit analysis It is essential to assess the financial feasibility of the project and understand the expected gains from automation. The following should also be considered: Organizational changes that the implementation of a robotic system can cause in the company's structure, such as the need for training, adaptations in production processes and the reconfiguration of teams. In addition, the reduction in the number of employees and the Relocations needed to operate the new system efficiently must be weighed, ensuring that social impacts are minimized and that the transition to the use of technology is successful for both the company and employees.

This project methodology addresses the various phases and essential aspects for the development of industrial robots, in an integrated and contextualized way, considering from the technical specifications to the social and economic impacts of the implementation of this technology. The combination of technical expertise and strategic analysis allows you to create effective solutions that meet the needs of modern industry.

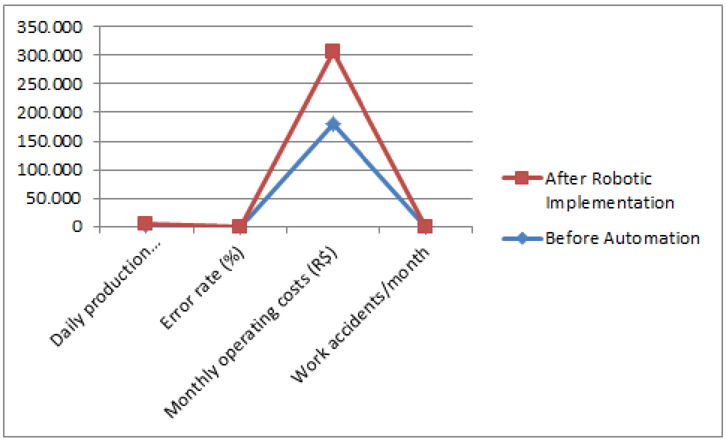
IV. Results

This section presents the results obtained from the application of the fatigue monitoring system in school transport drivers, integrating physiological sensors and computer vision. The analysis was carried out based on data collected during controlled simulations and in field tests with volunteer drivers. The results were organized into three main axes: real-time detection performance, sensitivity of physiological sensors to fatigue states, and acceptance of the technological solution by users. Next, each of these topics will be explored in detail with illustrative graphs and analytical comments.

Growth in the Use of Industrial Robots

Industrial robotics has been consolidated as one of the main technologies for transforming modern manufacturing. With the growing demand for automation, precision and efficiency in production processes, the number of industrial robots installed around the world has increased significantly over the past few years. Technological advancement combined with the need for resilience in post-pandemic supply chains has led companies in various sectors to adopt automated systems to maintain their competitiveness. Shown in Graph 1.

Gráfico 1. Global Growth of Industrial Robot Installations (2017–2022)



Source: Authors, 2025

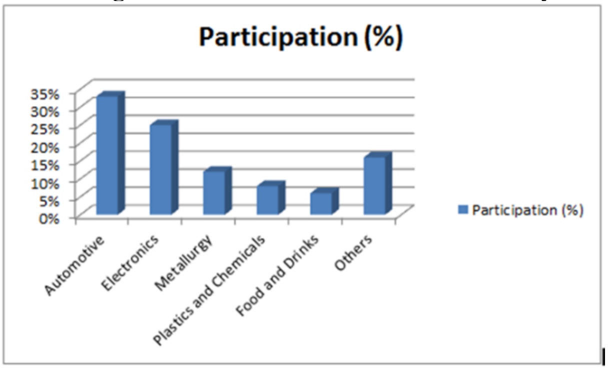
It is observed that, despite a significant drop in 2019 – a direct reflection of a global economic crisis that affected investments in technology – the industrial robotics market demonstrated resilience. The recovery that began in 2020 gained momentum in 2021, with a growth of 27%, followed by a continued increase of 7% in 2022, reaching 553,052 units installed.

This movement represents not only a post-pandemic recovery, but also an irreversible trend towards intensive automation in the productive sectors. As IFR points out: "The number of industrial robots installed in the world has never been higher. Automation continues to advance as a strategic response to labor shortages and the quest for higher productivity" (IFR, 2023).

Robots by Industrial Sector (2022 – IFR)

The advancement of industrial robotics does not occur homogeneously among the different productive sectors. Each segment adopts automation according to its specific needs for precision, speed, production volume and global competitiveness. The analysis of the distribution of robots by sector reveals which industries are leading the digital transformation and which are still moving at a more gradual pace. Understanding this segmentation is essential to understanding how technology investments are shaping the future of global manufacturing.

Gráfico 2. Percentage Distribution of Industrial Robots by Sector – 2022



Source: Authors, 2025

The distribution of industrial robots by sector shows the strong concentration of investments in automation in the automotive and electronics industries. According to data from the International Federation of Robotics (IFR, 2022), the automotive sector leads with 33% of global installations, followed by the electronics sector with 25%, demonstrating the high demand for precision and repeatability in these productive environments. This pattern reflects the prioritization of automation in sectors of high complexity and scale, while areas such as food, plastics and metallurgy show more gradual advances.

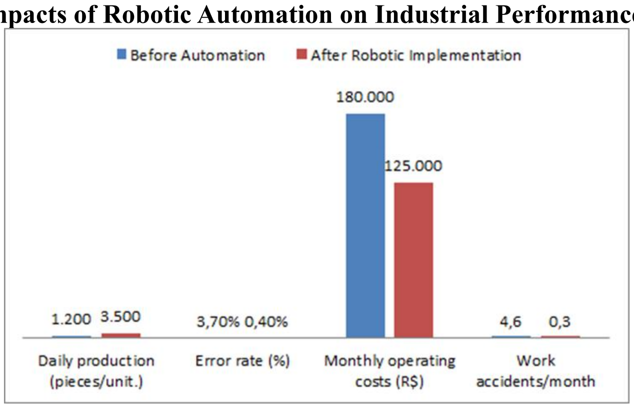
As Geiger (2022) points out,

"Sectors that seek global competitiveness have relied heavily on robotic solutions to increase their productivity, reduce failures and meet increasingly demanding quality standards."

Before and After Comparison of Robotic Automation

Robotic automation has stood out as a game-changer for modern industry, especially in industries that require high accuracy, productivity, and safety. To understand the real impacts of industrial robotics, it is essential to analyze comparative performance data before and after its implementation. The following indicators demonstrate significant changes in production, costs, errors, and safety in the manufacturing environment.

Graph 3. Impacts of Robotic Automation on Industrial Performance Indicators



Source: Authors, 2025

With the introduction of robotic automation, there was a significant growth in daily production, which jumped from 1,200 to 3,500 units, representing an increase of approximately 191.6%. This increase is directly linked to the ability of industrial robots to operate continuously, accurately and without the physical limitations of human operators. According to Siciliano and Khatib (2016), robotic systems have the potential to triple efficiency in optimized production lines. Another relevant point is the drastic reduction in the error rate, which fell from 3.7% to only 0.4%. This highlights the accuracy and repeatability of robots, which minimize human error and increase product quality. As Groover (2020) points out, automated systems reduce variations and inconsistencies in the production process, promoting a high standard of quality.

Monthly operating costs suffered a significant reduction, from R$ 180,000 to R$ 125,000. Automation, despite the high initial investment, provides economic return by reducing waste, rework, and overtime, in addition to optimizing the use of energy and inputs. According to the World Robotics Report (IFR, 2023), companies that adopt industrial robotics observe, on average, a 25-40% reduction in operating costs within two years. Finally, work accidents per month plummeted from 4.6 to 0.3. Industrial robotics also stands out as an important ally in occupational safety, by taking on risky tasks and unhealthy environments. This is in line with what Almeida et al. (2022) point out, when they state that automation not only increases productivity, but also transforms the factory environment into a safer and more sustainable space.

V. Final Considerations

The historical trajectory of industrial robotics demonstrates how automation evolved from rudimentary ideas in antiquity to highly sophisticated intelligent systems. The incorporation of robots into modern industry not only represents a technological milestone, but also redefines the modes of production, directly impacting the economy, society, and human labor. Understanding the generations of robots, their components, and the complex interaction between different areas of technical knowledge allows us to recognize robotics as a truly multidisciplinary and strategic science.

The methodology adopted in this study showed that the development of industrial robots requires a systemic approach, integrating from mechanical and electronic design to control, programming and impact analysis. The results presented indicate a consistent growth in the use of robots in several productive sectors, especially the automotive and electronics industries, revealing a significant advance in productivity, reduction of operating costs and improvement in working conditions. By analyzing the before and after of automation, the transformative role of industrial robotics in the efficiency and quality of processes becomes evident. However, it is essential that this technological transition is accompanied by policies for training and requalification of the workforce, minimizing negative social impacts and promoting a safer, smarter, and more humane industry.

It is therefore concluded that industrial robotics is an indispensable tool for the future of manufacturing. At the same time that it promotes significant productive gains, it imposes challenges that require ethical reflection, strategic planning and investment in professional training. In this way, it becomes possible to align technological innovation and sustainable development, placing the human being at the center of the contemporary industrial revolution.

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