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INDUSTRIAL ROBOTS AND THEIR ADVANCED APPLICATION

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Abstract: This review is dedicated to the advanced applications of robotic technologies in the industrial field. Robotic solutions in areas with non-intensive applications are presented, and their implementations are analyzed.

Analysis of robot applications shows that the existing emerging applications in robotics face technical and psychological obstacles. The results of this review revealed four directions of required advancement in robotics: development of intelligent companions; improved implementation of AI-based solutions; robot-oriented design of objects; and psychological solutions for robot-human collaboration.

Keywords: industrial robots; collaborative robots; machine learning in robotics; computer vision

1. Introduction

The industrial robotics sector is one of the most quickly growing industrial divisions, providing standardized technologies suitable for various automation processes. In ISO 8373:2012 standard, an industrial robot is defined as an automatically controlled, reprogrammable, multipurpose manipulator, programmable in three or more axes, which can be stationary or mobile for use in industrial automation applications. However, the same standard creates an exception for wider implementation. It states that the robot's classification into industrial, service, or other types is undertaken according to its intended application.

According to the International Federation of Robotics (IRF), 373,000 industrial robots were sold globally in 2019. In 2020 the total number of industrial robots operating in factories globally reached 2.7 million. Successful application of industrial robots, their reliability and availability, and the active implementation of the Industry 4.0 concept have stimulated growing interest in robots' optimization and the research of new implementations

in various areas, especially in non-manufacturing and non-typical applications.

According to one of the biggest scientific databases, ScienceDirect, more than 4500 scientific papers were published in 2019 using the term "Industrial robot" as a keyword and, in 2020, the number of papers with a similar interest and research direction increased to 5300. Figure 1 shows the annual ratio of new robot installations vs. the number of scientific publications in the ScienceDirect database. Scientific interest in this field is based on a steady increase in the number of publications, independent of the political, economic, and social factors affecting the market for new robots.

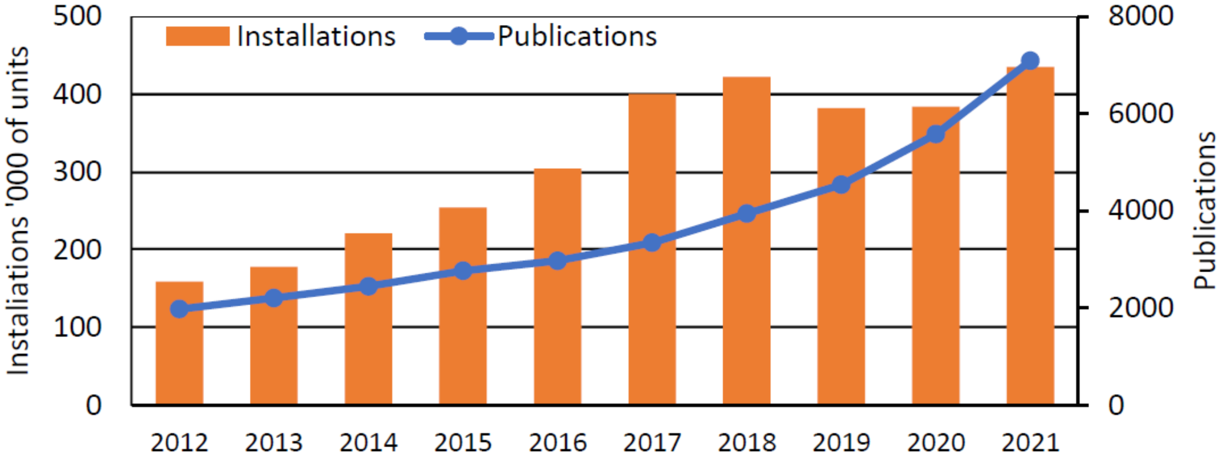

Figure 1. The annual ratio of publications to newly installed industrial robots.

This review assesses the recent development trends in robotics and identifies some of the most relevant ethical, technological and, scientific uncertainties limiting wider implementation possibilities. This literature review is focused mainly on the 2018–2021 applications of industrial robots in fields in which endorsement of robotization has traditionally been weak (i.e., medical applications, the food industry, agricultural applications, and the civil engineering industry). It also includes fundamental issues such as human-machine interaction, object recognition, path planning, and optimization.

For this review, main keywords, such as industrial robots, collaborative robots, and robotics, were used to survey published papers over four years. Because this is a widely researched and dynamic area, the review focused on a relatively short period and encompassed the most recent sources to ensure the analysis conducted was novel.

According to the search request, Google Scholar returned 79,500 results, from which 115 publications were selected. The surveyed articles were selected according to the direction of the literature review and the indicated criteria (application area, novelty and significance of achievements, reliability, and feasibility of results).

Despite the ever-growing field of automation in daily life and society's accustomed use of smart devices, non-typical applications of robotics are still often viewed with considerable skepticism. The most common myth about robots is that they will occupy human workplaces, leaving human workers without a source of livelihood. Nevertheless, the research provided which aimed to evaluate the public outcry about robots taking over jobs in electronics and textiles industries in Japan, proved that such a point of view is incorrect. Evaluation of the use of the robots based on their number and real implementation price determined that implementation of robots positively affects productivity, which results in a positive impact for the most vulnerable workers in society, i.e., women, part-time workers, high-school graduates, and aged persons.

Technological and scientific uncertainties also require a special approach. Each robotization task is unique in its own way. These tasks often require the use of individual tools, the creation of a corresponding working environment, the use of additional sensors or measurement systems, and the implementation of complex control algorithms to expand the functionalities or improve the characteristics of standard robots. In most applications, industrial robots form bigger units as robotic cells or automated/autonomous manufacturing lines. As a result, the robotization of even a relatively simple task becomes a complex solution requiring a systemic approach.

Moreover, the issue of implementing an industrial robot remains complicated by its interdisciplinary nature: proper organization of the work cycle is the object of manufacturing management sciences; the design of grippers and related equipment lies within the field of mechanical engineering; and the integration of all devices into a united system, sensor data analysis and whole system control are the objects of mechatronics.

The aim was to systematically classify the newest achievements in industrial robotics according to application fields without strong robotization traditions. The analysis of this study was also undertaken from a multidisciplinary perspective and considers the implementation of computer vision and machine learning for robotic applications.

2. Main Robotization Strategies

According to the human-robot cooperation type, a review of the most recent trends in industrial robotics applications indicates two main robotization strategies: classical and modern. In industrial robotics, five typical levels of human-robot cooperation are defined (Figure 2): (i) no collaboration; (ii) coexistence; (iii) synchronization; (iv) cooperation.
(v) collaboration.

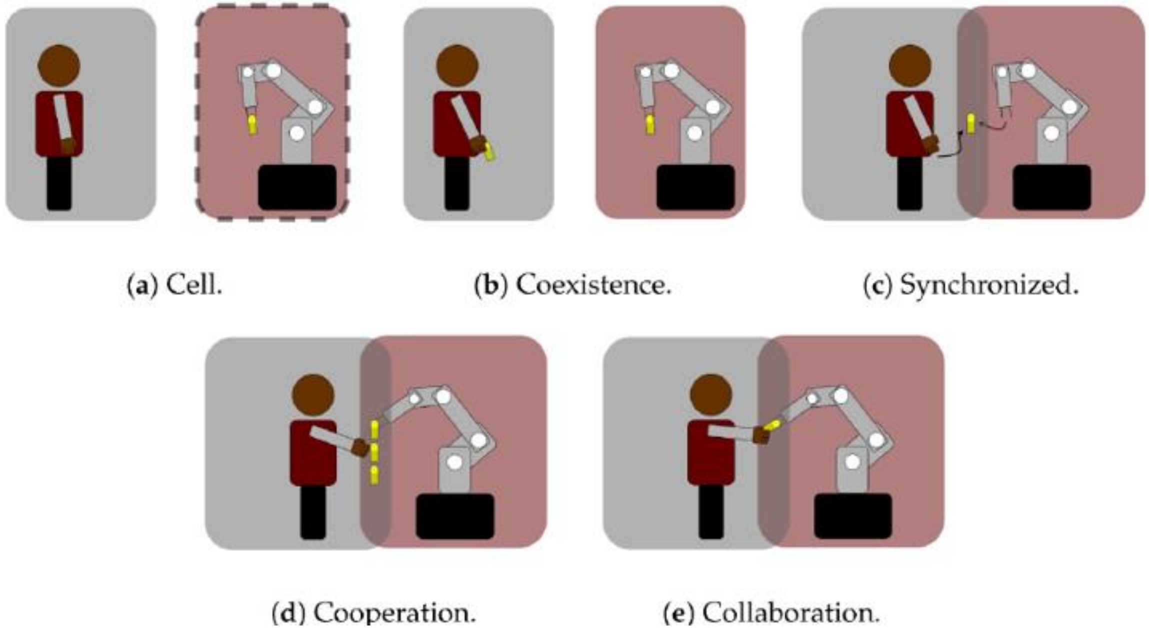

Figure 2. Human-robot cooperation levels: (**a**) no collaboration, the robot remains inside a closed work cell; (**b**) coexistence, removed cells, but separate workspaces; (**c**) synchronization, sharing of the workspace, but never at the same time; (**d**) cooperation, shared task and workspace, no physical interaction; (**e**) collaboration, operators and robots exchange forces.

The classical strategy encompasses the first cooperation level (Figure 2a). It is based on the approach that robots must limit humans in their workplace by creating closed robot cells in which human activity is unacceptable; if a human must enter the robot's workspace, the robot must be stopped. This approach uses various safety systems to detect and prevent human access to the robot's workspace. The modern strategy includes the remaining four cooperation levels (Figure 2b–e).

This is based on an opposing approach and states that robots and humans can work in one workplace and collaborate. Such an approach creates additional requirements for the robot's design, control, and sensing systems. Robots adapted to operate in conjunction with human workers are usually defined as collaborative robots. or cobots.

2.1. Classical Robotization Strategy

Following the issuing of the patent for the first industrial robot to George Devol in 1954, the classical robotization strategy has indicated that robots should replace human workers in routine tasks and unhealthy workplaces. This strategy suggests that humans should be removed from the robot's workspace (Figure 3a). Direct cooperation between the robot and humans is forbidden due to the potential danger to human health and safety. This approach was later expanded to encompass accuracy, reliability, productivity, and economic factors.

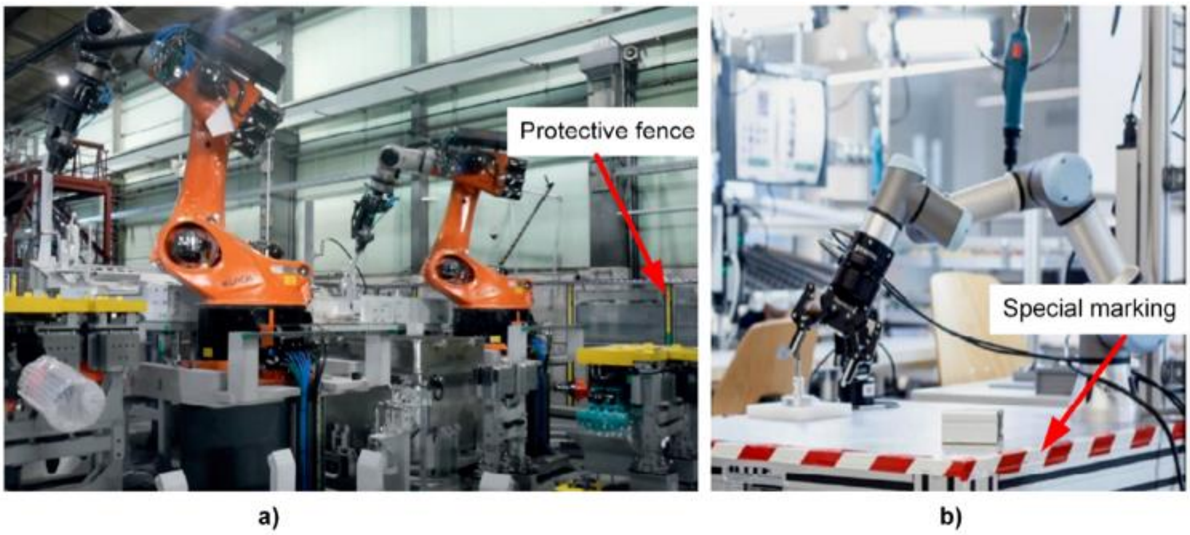

Figure 3. Comparison of the operating environment: (**a**) industrial robots (adapted from [6]) (**b**) collaborative robots (adapted from [7]).

Research provided analyses of the possibilities of implementing service robots in hotels from social, economic, and technical perspectives. The authors indicated the need to evaluate hotel managers' perceptions regarding the advantages and disadvantages of service robots, compared to human workers, as the primary goal of their research, whereas determining tasks suitable for robotization was of secondary importance.

This approach confirms the assumption that the implementation of robotics in non-traditional applications is often limited not by technological issues, but by the company managers' attitudes. Analyzing questionnaires completed by 79 hotel managers, it was concluded that robots have an advantage over human employees due to better data processing capabilities, work speed, protection of personal data, and fewer mistakes. The main disadvantages of robots were listed as lack of capability to provide personalized service; inability to handle complaints; lack of friendliness and politeness; inability to implement a special request that goes beyond their programming; and the lack of understanding of emotions.

Despite the common doubts, implementing automation and robotic solutions has a positive impact in many cases. The study provided in analyzed the general impact of robot implementation in workplaces for packing furniture parts. The analysis focused on the ergonomic perspective and found that the implementation of robotics eliminates the risk of work-related musculoskeletal disorders. A similar study analyzed the design, engineering, and testing of adaptive automation assembly systems to increase automation levels and complement human workers' skills and capabilities in assembling industrial refrigerators. This study showed that automated assembly process productivity could be increased by more than 79%. Implementing an industrial robot instead of partial automation would likely result in an even more significant increase in productivity. Research comparing human capabilities with automated systems is also described. The authors compared human and automated vision recognition system capabilities to recognize and evaluate forest or mountain trails from a single monocular image acquired from the viewpoint of a robot travelling on the trail. The obtained results showed that a deep neural network-based system, trained on a large dataset, performs better than humans.

The classic strategy is well suited to the robotization of mass production processes in various fields and its main advantages are clear requirements for work process organization, robotic cell design, and installation; the availability of a large variety of standard equipment and typical partial solutions; and higher productivity and reliability compared to the cases where human workers perform the same tasks. The main disadvantages are insufficient flexibility, unsuitability for unique production, and high economic costs when it is necessary to adapt the existing robotic cell to a new product or process.

Applying a modern robotization strategy can avoid some of these disadvantages (or at least minimize their impact).

2.2. Modern Robotization Strategy

The modern robotization strategy is based on implementing collaborative robots (cobots). According to the definition of cobot was first used in a 1999 US patent and was intended for “an apparatus and method for direct physical integration between a person and a general-purpose manipulator controlled by a computer.” It was the result of the efforts of General Motors to implement robotics in the automotive sector to help humans in assembly operations. The first lightweight cobot, LBR3, designed by a German robotics company, was introduced in 2004. This has led to the broader development of a modern robotics strategy and new manufacturers in the market. In 2008, the Danish manufacturer Universal Robots released the UR5, a cobot that could safely operate alongside the employees, eliminating the need for safety caging or fencing (Figure 3b). This launched a new era of flexible, user-friendly, and cost-efficient collaborative robots, and resulted in the current situation, in which all of the major robot manufacturers have at least a few cobot models in their product range.

The fourth industrial revolution—Industry 4.0—significantly fostered the development of Cobot’s technologies, because the concept fitted well with Industry 4.0 content, allowing human-robot collaboration to be realized and being suitable for flexible manufacturing systems. Contrary to typical industrial robots, next-generation robotics uses artificial intelligence (AI) to collaboratively perform tasks and is suitable for uncontrolled/unpredictable environments. Moreover, due to favorable conditions (advances in AI, sensing technologies, and computer vision), collaborative industrial robots have become significantly smarter, showing the potential for reliable and secure cooperation, and increasing the productivity and efficiency of the involved processes. However, it should be noted that Industry 4.0 fostered not only the widespread of robotics but also posed new challenges.

When developing highly automated systems, most of the equipment is related to the Internet of Things (IoT) or other communication technologies. Therefore, cybersecurity and privacy protection of processes used to monitor and control data must be considered.

The issue of data protection is also becoming more critical due to the latest communication technologies, such as 5G and 6G. These technologies allow the development of standardized wireless communication networks for various control levels (single-cell, production line, factory, network of factories) and, at the same time, make systems more sensitive to external influences. The main impact of Industry 4.0 and new communication technologies on industrial robots is that their controllers have an increasing number of connections, functions, and protocols to communicate with other “smart” devices.

Compared to traditional industrial robots, cobots have more user-friendly control features and wider teaching options. A new assembly strategy was described in a previous study, in which a cobot learnt skills from manual teaching to perform peg-in-hole automatic assembly when the geometric profile and material elastic parameters of parts were inaccurate. The results showed that the manual assembly process could be analyzed mathematically, splitting it into a few stages and implementing it as a model in robot control. Using an Elite EC75 manipulator (Elite Robot, Suzhou, CN, an assembly time of less than 20 s was achieved, ensuring a 100% success rate from 30 attempts when the relative error between the peg and hole was _4.5 mm, and the clearance between the peg and the hole was 0.18 mm.

As a result of the development of sensor and imaging technologies, new applications in robotics are emerging, especially in human-robot collaboration. In, detailed research focused on identifying the main strengths and weaknesses of augmented reality (AR) in industrial robot applications. The analysis shows that AR is mainly used to control and program robotic arms, visualize general tasks or robot information, and visualize the industrial robot workspace. Results of the analysis indicate that AR systems are faster than traditional approaches; users have greater appreciation for AR systems in terms of likeability and usability; and AR seems to reduce physical workload, whereas the impact on mental workload depends on the interaction interface. Nevertheless, industrial implementation of AR is still limited by insufficient accuracy, occlusion problems, and the limited field of view of wearable AR devices.

A summary of the analyzed robotization strategies indicates that they both have their specific implementation fields. The classical strategy is well suited to strictly controlled environments. The modern strategy ensures more flexible operation and is suitable for non-predictable environments. Nevertheless, it is necessary to note that the strict line between these strategies has gradually disappeared due to advances in sensing technologies, artificial intelligence, and computer vision. A typical industrial robot equipped with modern sensing and control systems can operate similarly to a cobot. According to, collaborative regimes can be realized using industrial robots, laser sensors, vision systems, or controller alteration if compliance with the ISO/TS 15066 standard—which specifies parameters and materials adapted to safe activities with and near humans—is ensured.

This standard defines four main classes of safety requirements for collaborative robots: safety-rated monitored stop; hand-guiding; speed and separation monitoring; and power and force limiting. In addition, it is essential to mention that all improvements and advances in robotics

can be classified into two main types: universal and application-dependent. The remaining part of this article reviews and classifies the latest advances in robotics according to the areas of their implementation.

3. Recent Achievements in Industrial Robotics Classified according to Implementation Area

3.1. Human–Machine Interaction

To date, manual human work has been often replaced by robotic systems in the industry. However, within complex systems, the interaction between humans and machines/robots (HMI) still needs to occur. HMI is an area of research related to the development of robotic systems based on understanding, evaluation, and analysis, and this system combines various forms of cooperation or interaction with humans. Interaction requires communication between robots and humans, and human communication and collaboration with the robot system can take many forms. However, these forms are greatly influenced by whether the human is close to the robot and the context being used: (i) human-computer context—keyboard, buttons, etc.; (ii) real procedures context—haptics, sensors; and (iii) close and exact interaction. Therefore, both human and robot communication or interaction can be divided into two main categories: remote interaction and exact interaction. Remote interaction takes place by remote operation or supervised control. Close interaction takes place by operation with an assistant or companion. Close interaction may include physical interaction. Because close interactions are the most difficult, it is crucial to consider several aspects to ensure successful collaboration, i.e., a real-time algorithm, “touch” detection and analysis, autonomy, semantic understanding capabilities, and AI-aided anticipation skills.

The interaction between humans and robots or mechatronic systems encompasses many interdisciplinary fields, including physical sciences, social sciences, psychology, artificial intelligence, computer science, robotics, and engineering. This interaction examines all possible situations in which a human and a robot can systematically collaborate or complement each other. Thus, the main goal is to provide robots with various competencies to facilitate their interaction with humans. To implement such competencies, modelling of real-life situations and predictions is necessary, as applying models in interaction with robots and trying to make this interaction as efficient as possible, i.e., inherently intuitive, based on human experience and artificial intelligence algorithms.

3.2. Object Recognition

Object recognition is a typical issue in industrial robotics applications, such as sorting, packaging, grouping, picking and placing, and assembling. The appropriate recognition method and equipment selection mainly depend on the given task, object type, and the number of recognizable parameters. If there are a small number of parameters, simpler sensing technologies based on typical approaches (geometry measuring, weighing, material properties’ evaluation) can be implemented. Alternatively, if there are a significant number of recognizable parameters, photo or video analysis is preferred.

Required information in two- or three-dimensional form from images or video can be extracted using computer vision techniques such as object localization and recognition. Various techniques of vision-based object recognition has been developed, such as appearance-, model-, template-, and region-based approaches. Most vision recognition methods are based on deep learning and other machine learning methods.

In a previous study, a lightweight Franka Emika Panda, cobot with seven degrees of freedom and a RealSense D435 RGB-D camera, mounted on an end effector, was used to extend the default robots' function. Instead of using a large dataset-based machine learning technique, the authors proposed a method to program the robot from a single demonstration. This robotic system can detect various objects, regardless of their position and orientation, achieving an average success rate of more than 90% in less than 5 min of training time, using an Ubuntu 16.04 server running on an Intel(R) Core(TM) i5-2400 CPU (3.10 GHz) and an NVIDIA Titan X GPU.

Another approach for grasping randomly placed objects was presented in the author's proposed set of performance metrics and compared four robotic systems for bin picking, and took first place in the Amazon Robotics Challenge 2017. The survey results show that the most promising solutions for such a task are RGB-D sensors and CNN-based algorithms for object recognition, and a combination of suction-based and typical two-finger grippers for grasping different objects (vacuum grippers for stiff objects with large and smooth surface areas, and two-finger grippers for air-permanent items).

Similar localization and sorting tasks appear in the food and automotive industries and in almost every production unit. In an experimental method was proposed using a pneumatic robot arm for the separation of objects from a set according to their colour. If the colour of the workpiece is recognizable, it is selected with the help of a robotic arm. If the workpiece colour does not meet the requirements, it is rejected. The described sorting system works according to an image processing algorithm in MATLAB software. More advanced object recognition methods based on simultaneous colour and height detection are presented in. A robotic arm with six degrees of freedom (DoF) and a camera with computer vision software ensure a sorting efficiency of about 99%.A Five DoF robot arm, “OWI Robotic Arm Edge”, proposed by Pengchang Chen et al., was used to validate the practicality and feasibility of a faster region-based convolutional neural network (faster R-CNN) model using a dataset containing images of symmetric objects. Objects were divided into classes based on colour, and defective and nondefective objects.

Despite significant progress in existing technologies, randomly placed unpredictable objects remain a challenge in robotics. The success of a sorting task often depends on the accuracy with which recognizable parameters can be defined. Yan Yu et al proposed an RGB-D-based method for solid waste object detection. The waste sorting system consists of a server, vision sensors, industrial robots, and a rotational speedometer. Experiments performed on solid waste image analysis resulted in a mean average precision value of 49.1%. Furthermore, Wen Xiao et al. designed an automatic sorting robot that uses height maps and near-infrared (NIR) hyperspectral images to locate the region of interest (ROI) of objects, and to perform online statistic pixel-based classification in contours. This automatic sorting robot can automatically sort construction and demolition waste ranging in size from 0.05 to 0.5 m. The online recognition accuracy of the developed sorting system reaches almost 100% and ensures an operation speed up to 2028 picks/h.

Another challenging issue in object recognition and manipulation is objects having an undefined shape and being contaminated by dust or smaller particles, such as minerals or coal. Quite often, such a task requires not only recognizing the object but also determining the position of the centre of mass of the object. Man Li et al proposed an image-processing-based coal and gangue sorting method. Particle analysis of coal and gangue samples is performed using morphological corrosion and expansion methods to obtain a complete, clean target sample. The object's mass centre is obtained using the centreof the mass method, consisting of particle removal and filling, image binarization, and separation of overlapping samples, reconstruction, and particle analysis. The presented method achieved identification accuracy of coal and gangue samples of 88.3% and 90.0%, and the average object mass centre coordinate errors in the x and y directions were 2.73% and 2.72%, respectively.

Intelligent autonomous robots for picking different kinds of objects were studied as a possible means to overcome the current limitations of existing robotic solutions for picking objects in cluttered environments. This autonomous robot, which can also be used for commercial purposes, has an integrated two-finger gripper and a soft robot end effector to grab objects of various shapes. A special algorithm solves 3D perception problems caused by messy environments and selects the right grabbing point. When using lines, the time required depends significantly on the configuration of the objects and ranges from 0.02 s when the objects have almost the same depth, to 0.06 s in the worst case when the depth of the tactile objects is greater than the lowest depth but not perceived.

In robotics, the task of object recognition often includes not only recognition and the determination of coordinates, but it also plays an essential role in the creation of a robot control program. Based on the ABB IRB 140 robot and a digital camera, a low-cost shapes identification system was developed and implemented, which is particularly important due to the high variability of welded products. The authors developed an algorithm that recognizes the required toolpath from a taken image. The algorithm defines a path as a complex polynomial. It later approximates it by simpler shapes with a lower number of coordinates (line, arc, spline) to realize the tool movement using standard robot programming language features.

Moreover, object recognition can be used for robot machine learning to analyze humans' behaviour. Such an approach was presented by Hiroaki et al , where the authors studied the behaviour of a human crowd, and formulated a new forecasting task, called crowd density forecasting, using a fixed surveillance camera. The main goal of this experiment was to predict how the density of the crowd would change in unseen future frames. To address this issue, patch-based density forecasting networks (PDFNs) were developed. PDFNs project a variety of complex dynamics of crowd density throughout the scene, based on a set of spatially or spatially overlapping patches, thus adapting the receptive fields of fully convolutional networks. Such a solution could be used to train robotic swarms because they behave similarly to humans in crowded areas.

A few main trends can be highlighted from the research analysis related to object recognition in robotics. These can be defined as object recognition for localization and further manipulation; object recognition for shape evaluation and automatic generation of the robot program code for the corresponding robot movement; and object recognition for behaviour analysis to use as initial data for machine learning algorithms. A large number of reliable solutions have been tested in the industrial environment for the first trend, in contrast to the second and third cases, which are currently being developed.

3.3. Medical Application

The da Vinci Surgical System is the best-known robotic manipulator used in surgery applications. Florian Richter et al presented a Patient Side Manipulator (PSM) arm technology to implement reinforcement learning algorithms for the surgical da Vinci robots. The authors presented the first open-source reinforcement learning environment for surgical robots, called dVRL. This environment allows fast training of da Vinci robots for autonomous assistance, and collaborative or repetitive tasks, during surgery. During the experiments, the dVRL control policy was effectively learned, and it was found that it could be transferred to a real robot- with minimal effort. Although the proposed environment resulted in the simple and primitive actions of reaching and picking, it was useful for suction and debris removal in a real surgical setting.

Meanwhile, in their work, Yohannes Kassahun et al. reviewed the role of machine learning techniques in surgery, focusing on surgical robotics. They found that currently, the research community faces many challenges in applying machine learning in surgery and robotic surgery. The main issues are a lack of high-quality medical and surgical data, a lack of reliable metrics that adequately reflect learning characteristics, and a lack of a structured approach to the effective transfer of surgical skills for automated execution. Nevertheless, the application of deep learning in robotics is a very widely studied field. The article by Harry A. Pierson et al. in 2017 provides a recent review emphasizing the benefits and challenges vis-à-vis robotics. Similarly, they found that the main limitations preventing deep learning in medical robotics are the huge volume of training data required and a relatively long training time.

Surgery is not the only field in medicine in which robotic manipulators can be used. Another autonomous robotic grasping system, described by John E. Downey et al., introduces shared control of a robotic arm based on the interaction of a brain-machine interface (BMI) and a vision-guiding system. A BMI is used to define a user’s intent to grasp or transfer an object. Visual guidance is used for low-level control tasks, short-range movements, definition of the optimal grasping position, alignment of the robot end-effector, and grasping. Experiments proved that shared control movements were more accurate, efficient, and less complicated than transfer tasks using BMI alone.

Another case that requires fast robot programming methods and is implemented in medicine is the assessment of functional abilities in functional capacity evaluations (FCEs). Currently, there is no single rational solution that simulates all or many of the standard work tasks that can be used to improve the assessment and rehabilitation of injured workers. Therefore, the authors proposed that, with the use of the robotic system and machine learning algorithms, it is possible to simulate workplace tasks. Such a system can improve the assessment of functional abilities in FCEs and functional rehabilitation by performing reaching manoeuvres or more complex tasks learned from an experienced therapist. Although this type of research is still in its infancy, robotics with integrated machine-learning algorithms can improve the assessment of functional abilities.

Although the main task of robotic manipulators is the direct manipulation of objects or tools in medicine, these manipulators can also be used for therapeutic purposes for people with mental or physical disorders. Such applications are often limited by the ability to automatically perceive and respond as needed to maintain an engaging interaction. Ognjen Rudovic et al. presented a personalized deep-learning framework that can adapt robot perception.

The researchers in the experiment focused on robot perception, for which they developed an individualized deep learning system that could automatically assess a patient’s emotional states and level of engagement. This makes it easier to monitor treatment progress and optimize the interaction between the patient and the robot. It can be seen that robots are still not very popular in this area, and technological and psychological/ethical factors can explain this. From the technical point of view, more active implementation is limited by the lack of fast and reliable robot program preparation methods. Regarding psychological and ethical factors, robots are still unreliable for a large portion of society. Therefore, they are only accepted with significant hesitation.

3.4. Path Planning, Path Optimization

The process known as robotic navigation aims to achieve accurate positioning and avoid obstacles in the pathway. It is essential to satisfy constraints such as limited operating space, distance, energy, and time. The path trajectory formation process consists of these four separate modules: perception, when the robot receives the necessary information from the sensors; localization, when the robot aims to control its position in the environment; path planning; and motion control. The development of autonomous robot path planning and path optimization algorithms is one of the most challenging current research areas. Nevertheless, any kind of path planning requires information about the initial robot position. In the stationary robot’s case, such information is usually easily accessible, contrary to industrial manipulators mounted on mobile platforms. In mobile robots and automatically guided vehicles (AGV), accurate self-localization in various environments is a basis for further trajectory planning and optimization.

According to the amount of available information, robot path planning can be categorized into two categories, namely, local and global path planning. Through a local path planning strategy, the robot has rather limited knowledge of the navigation environment. The robot has in-depth knowledge of the navigation environment when planning the global path to reach its destination by following a predetermined path. The robotic path planning method has been applied in many fields, such as reconstructive surgery, ocean and space exploration, and vehicle control. In the case of pure industrial robots, path planning refers to finding the best trajectory to transfer a tool or object to the destination in the robot workspace. It is essential to note that typical industrial robots are not feasible for real-time path planning. Usually, trajectories are prepared in advance using online or offline programming methods. One of the possible techniques is the implementation of specialized commercial computer-aided manufacturing (CAM) software such as Mastercam/ Robotmaster or Sprutcam. However, the functionality of such software is relatively constrained and does not go beyond the framework of classical tasks, such as welding or milling. The use of CAM software also requires highly qualified professionals. As a result, the application of this software to individual installations is economically disadvantageous. As an alternative to CAM software, methods based on the copying movements of highly skilled specialists using commercially available equipment, such as MIMIC from Nordbo Robotics (Antvorskov, Denmark), may be used. This platform allows demonstrations to teach robots smooth, complex paths by recording required movements that are smoothed and optimized. To overcome the limitations caused by the lack of real-time path planning features in robot controllers, additional external controllers and real-time communication with the manipulator are required. In the area of path planning and optimization, experiments have been conducted for automatic object and 3D position detection quasi-static path optimization, image analysis, path smoothing, BIM, and accurate self-localization in harsh industrial environments.

Although the food industry is ranked fourth in terms of the most automated sectors, robotic devices capable of processing nutrients of different shapes and materials are in high demand. In addition, these devices help to avoid consequences such as food-borne illness caused directly by the contamination of nutrients by nutrient handlers. For this purpose, a dual-mode soft gripper was developed that can grasp and suck various objects weighting up to 1 kg. Soft grippers prevent damage to food.

Artificial intelligence-enabled robotic applications are entering the restaurant industry in food processing and guest service operations. In a review assessing the potential for process innovation in the restaurant sector, an information process for the use of new technologies for process innovation was developed. However, the past year, particularly due to the circumstances of COVID-19, has been a breakthrough year in robotization in the food industry.

3.5. Agricultural Applications

Agricultural robots are a specialized type of technology capable of assisting farmers with a wide range of operations. Their primary role is to tackle labour-intensive, repetitive, and physically demanding tasks. Robots are used in planting, seedling identification, and sorting. Autonomous tractors perform the function of weeding and harvesting. Drones and autonomous ground vehicles are used for crop monitoring and condition assessment. In animal husbandry, robots are used for feeding cattle, milking, collecting and sorting eggs, and autonomous cleaning of pens. Cobots are also used in agriculture. These robots possess mechanical arms and make harvesting much easier for farmers. The agriculture robot market size is expected to reach USD 16,640.4 billion by 2026; however, specific robots, rather than industrial robots, will occupy the majority of the market.

3.6. Civil Engineering Industry

In general, the construction industry is relatively inefficient from the perspective of automation. Robotics are seldom applied. The main identified challenges for higher adoption of robotics in the construction industry were grouped into four categories: contractor-side economic factors; client-side economic factors; technical and work-culture factors; and weak business case factors. Technical and work-culture factors include an untrained workforce; unproven effectiveness and immature technology; and the current work culture and aversion to change.

The perspective of robotics in civil engineering is significantly better. Here, robotics provides considerable opportunities to increase productivity, efficiency, and flexibility, from automated modular house production to robotic welding, material handling on construction sites, and 3D printing of houses or certain structures. Robots make the industry safer and more economical, increase sustainability, and reduce its environmental impact, while improving quality and reducing waste. The total global value of the construction industry is forecast to grow by 85% to USD 15.5 trillion by 2030. Robots can make construction safer by handling large and heavy loads, working in hazardous locations, and enabling new, safer construction methods. Transferring repetitive and dangerous tasks that humans are increasingly reluctant to perform to robots means that automation can help address the labour and skills crisis, and make the construction industry more

Attractive. Few classic robots are used in the construction process due to the dynamic and inaccurately described environment; however, work on 3D buildings and their environmental models reduce this limitation.

4. Discussion

Implementing an industrial robot in practice is a complex procedure that requires answering many questions about the possibilities of using the robot and the process itself. The situation varies slightly depending on the industry area. Robots have been used in some areas for 30 or more years, whereas, in other areas, the implementation of robots is only beginning. In industrial sectors with a long tradition of robotics, new solutions are relatively more straightforward. These solutions are typically limited to implementing new tools, control algorithms, and robotic action quality control systems. Therefore, our article focuses on areas where traditions of implementing robots do not exist yet, and such solutions are just beginning to be implemented.

Despite the different application areas, some achievements in robotics can be successfully transferred from one industry to another. Furthermore, bypassing limitations in one area often ensures advances in robotics in other sectors. For example, the implementation of computer vision to localize and manipulate randomly placed mechanical parts on a conveyor fostered the robotization of sorting processes in all industry fields. This article provided an overview of the main areas where robots are beginning to be implemented, and identified the main challenges and limitations they face (Figure 4).

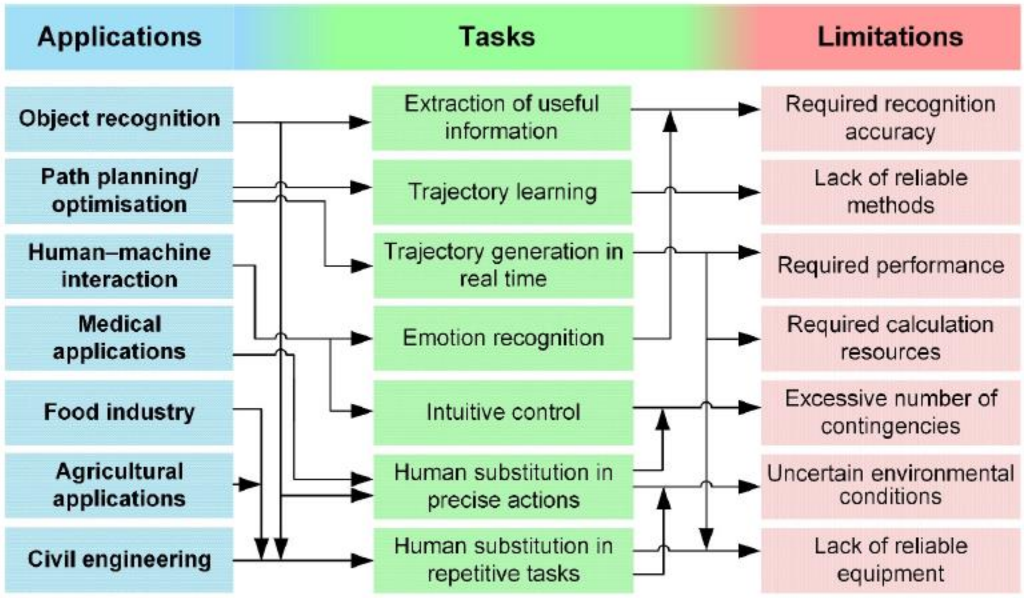

Figure 4. Relations between robot implementation areas, typical tasks and limitations.

The conclusion is that tasks performed by the robots and actual limitations are closely related to each other regardless of the implementation field. In this paper, the tasks for which robots are most preferred rather than humans were identified. Typically, these tasks are repetitive and extremely precise operations that require evaluating a considerable amount of data. For example, the implementation of robots for object recognition has three main functions in which robots replace humans: (1) extraction of useful information from massive data flow; (2) accurate movements to manipulate with an object

or tool; and (3) repetitive action (sorting). In addition, the food, agriculture, and civil engineering industries aim to replace humans involved in repetitive actions. In contrast, medical applications are mainly related to accurate manipulation and hazardous environments. Many different factors limit the implementation of industrial robots in typical tasks. The seven main limitations in the reviewed application fields were identified. In summary, the main limitations are the lack of suitable methods, high recognition accuracy, and
performance requirements; varying environmental conditions; an excessive number of possible situations; and lack of reliable equipment (tools). Notably, these limitations are unrelated to the robot’s mechanical systems (except the tools). Therefore, most modern robotic solutions are fostered by the development of additional equipment or control algorithms. Computer vision, sensor fusion, and machine learning are becoming major engines driving industrial robots’ wider application.

As a result of the development of robot control systems, robots’ internal structures have also been improved. These improvements typically include the implementation of new mathematical methods for robot control or optimization of energy consumption. For example, a previous study provided a methodology that allows the implementation of a non-typical Denavit–Hartenberg method for a delta robot. Nonetheless, despite the recent improvements and smart solutions realized in industrial robots, their widespread use in non-typical areas remains limited. The main limitations and guidelines for further research are new intuitive control methods, user-friendly interfaces,specialized software, and real-time control methods.

5. Conclusions

Analysis of robot applications revealed several important issues and showed that the current rare applications of robot implementations are not always limited by technical difficulties. Some application fields have no tradition in such activities, such as the civil engineering, food, and agriculture industries. Human-robot cooperation in classical industrial robots and in specialized cobot cases still demands an intensive introduction into these industries. However, in this case, the introduction involves non-technical spects such as human psychology and personal acceptance of the robots in their workplace. Another aspect of the subjective attitude to robots is limited by their acceptance by managers and process designers; however, they also lack implementation experience and knowledge of cutting-edge achievements in robotic applications. Many automation cases are still limited by artificial intelligence (AI) issues related to object recognition, object position recognition, and decision generation for object grabbing and manipulating. This issue arises from the process of widening robotic implementation in existing industries, and therefore many technologies should be redesigned. Nevertheless, pressure due to the absence of a skilled labour force has led to new solutions. Many general solutions using machine vision and sensor fusion (camera–lidar scanner, camera–distance sensors, etc.) have been spontaneously implemented in numerous industrial enterprises. These approaches are starting to appear in home appliances, but market penetration of these solutions remain low.

Robot implementations are often subject to systematic difficulties, such as manipulation and orientation of solid objects with non-stable geometrical shapes. These objects are widely used in industry and home appliances and include textiles, clothes, and cables. At present, this area has few publications and technical solutions, and is in the research stage; presentations of some of the publicly available cases are at the level of scientific publications. Although clamps and templates are currently used for specific industrial cases, general solutions have not yet been achieved. This situation requires rethinking processes and possibly preparing objects for robotic processing, rather than using tremendous computing and multiplying hardware.

The result of this review points to four evident directions in the field of robotics:
_ development of intelligent companion equipment for robots (sensors, grippers, and
servo-applications);
_ AI-based solutions for signal processing and decision-making;

_ the redesign of general objects and the related features for robotic applications;
_ provision of psychological solutions for robot-human collaboration and acceptance of robots in the workplace.

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