Baština Akademije nauka i umjetnosti Bosne i Hercegovine

SMART MANUFACTURING ON THE HORIZON: A Conceptual Shift from Industry 4.0 to Industry 5.0: Industrija

Karabegović, Isak

2026

Academy of Sciences and Arts of Bosnia and Herzegovina

https://bastina.anubih.ba/handle/123456789/875

Preuzeto s Baštine Akademije nauka i umjetnosti Bosne i Hercegovine

https://bastina.anubih.ba/

DOI: 10.5644/PI2026.225.03

Application of Augmented Reality in Collaborative Robots

Ermin Husak[*1]

Abstract: *Augmented Reality (AR) and collaborative robotics represent two interconnected technologies that play a significant role in the development of modern industrial production and the concept of Industry 4.0. Augmented reality enables the display of digital information in a real environment, which improves user interaction with production systems, while collaborative robots enable safe cooperation between humans and robots in a shared workspace. The paper presents the basic working principles of AR technology, its types and areas of application, as well as the characteristics of collaborative robots, their safety requirements and application possibilities in industry. A special emphasis is placed on the integration of these technologies, whereby augmented reality enables visualization of processes in real time, simpler programming of robots, simulation of work operations, increased safety, and more efficient training and technical support for operators. The analysis shows that the combination of AR technology and collaborative robotics contributes to increasing productivity, production quality, flexibility of production processes and safety of the working environment. The further development of these technologies, along with the application of artificial intelligence, machine vision and IoT systems, represents an important step towards the development of smart factories of the future.*

Keyword: *Collaborative Robotics, Cobots, Augmented Reality, Programming, Simulation*

1. Introduction

The development of digital technologies in recent years has significantly changed the way industrial production processes are organized and managed. The concepts of Industry 4.0 and Industry 5.0 are based on the integration of advanced information and communication technologies, automation, robotics and intelligent production systems with the aim of increasing productivity, quality and flexibility of production. In this context, Augmented Reality - AR and collaborative robotics, which represent one of the most promising technologies of contemporary industry, stand out. Augmented reality enables the display of digital content in a real environment, thus providing users with additional information and more intuitive interaction with production systems [1,2,3]. At the same time, collaborative robots enable safe cooperation between humans and robots in a shared workspace, combining human flexibility, creativity and decision-making

[*1]University of Bihać, Technical Faculty, Bihać, Bosnia and Herzegovina
E-mail: erminhusak@gmail.com

ability with the precision, speed and repeatability of robotic systems[4-7]. The aim of this paper is to present the basic characteristics of augmented reality and collaborative robotics, analyses their application possibilities in industry and point out the advantages of their mutual integration. Special attention is paid to the application of AR technology in the visualization of data in real time, programming of collaborative robots, simulation of production processes, increase of work safety and improvement of training and maintenance processes. The integration of these technologies represents an important step towards the development of intelligent, flexible and safe production systems of the future.

2. Augmented Reality – AR

Augmented Reality (AR) is a technology that allows overlaying digital content with the real environment in real time. Unlike virtual reality (VR), which fully immerses the user in a computer-generated environment, augmented reality maintains a view of the real world and simultaneously displays additional information, three-dimensional models, text, images or animations. The basic working principle of augmented reality is based on the use of cameras, sensors, processors and appropriate software that recognizes objects or the space in which the user is located. After recognizing the environment, the system adds virtual elements to the screen of a mobile phone, tablet, smart glasses or other device that are displayed as an integral part of the real environment. In this way, the user gets additional information without having to leave the real space. The application of augmented reality is very wide today. In education, it is used to display complex processes and phenomena through interactive 3D models, which enables pupils and students to understand the teaching content more easily. In industry and production, AR helps workers during assembly, maintenance and quality control by displaying instructions directly at the workplace. In medicine, it is used to plan operations, educate medical staff, and visualize the anatomical structures of patients. Significant applications of augmented reality are also present in marketing, retail, and the entertainment industry. Shoppers can virtually try on clothes, glasses, or furniture before making a purchase, while video game users can experience interactive content that is connected to the real environment.

Previously, augmented reality was considered complex to use, but today this is no longer the case. Using AR technology generally does not require special devices or special knowledge. Most modern mobile phones and laptops can use AR applications. Users can simply download the appropriate application and use augmented reality. Many believe that using augmented reality requires wearing special glasses or a helmet. It is true that AR glasses have become popular thanks to companies such as Microsoft and Google, but their use is not mandatory. Today, augmented reality content is most often displayed via mobile phones and tablets.

AR visualization technologies can be classified into four main categories: Head-Mounted Displays (HMDs), Hand-Held Displays (HHDs), Fixed or Static Screens, Spatial Displays (Figure1).

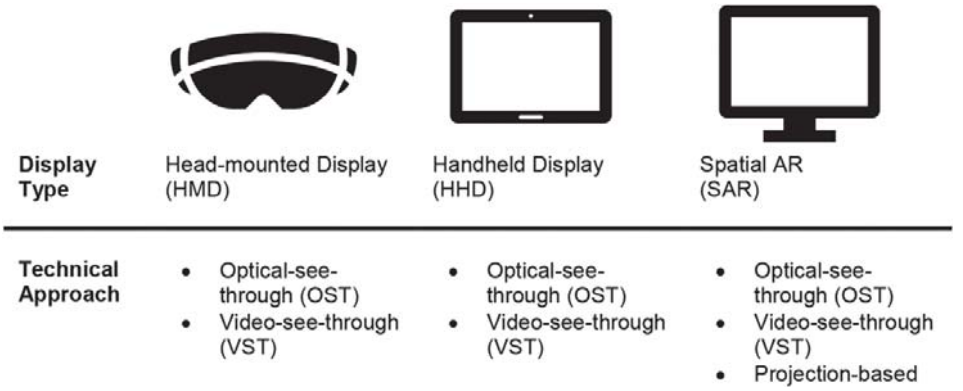

Figure 1: AR visualization technologies [1]

- Head-Mounted Displays (HMDs)

Head-Mounted Display (HMD) is a device that is worn on the head like glasses or a helmet and displays digital content directly in front of the user's eyes. It is used in virtual reality (VR) and augmented reality (AR) systems, enabling the display of three-dimensional objects, information and virtual environments while tracking the movements of the user's head.

Figure 2. Head-Mounted Displays

Examples of HMD devices are: Meta Quest 3, Apple Vision Pro, and HTC Vive.

- Hand-Held Displays (HHDs)

Hand-Held Displays (HHDs) in the context of augmented reality are hand-held devices that enable the display of digital information and virtual objects over an image of the real environment. The most common examples of HHD devices are smartphones and tablets (Figure 3). With the HHD system, the user holds the device in his hand, and the built-in camera records the real environment. The software then displays on the screen a combination of the real image and virtual elements, such as text, graphics, 3D models or animations. The advantages of HHD devices are wide availability because most users own a smartphone, relatively low price compared to AR glasses, simple use, the possibility of using existing cameras, sensors and GPS. The disadvantages of HHD devices are that the user must hold the device in his hand during use, a lower level of immersion compared to AR glasses, a limited field of vision, and hand fatigue during prolonged use.

Figure 3. HD AR application on Apple iPad 10.2"

- Fixed or Static Screens

These are televisions and computer monitors. They display extended content on fixed screens. They require additional recording and processing devices. They are limited to stationary applications and require the user's attention to be diverted.

- Spatial Displays

These are projectors that display content directly on real objects. They do not require user attention. They are suitable for team work, but are limited to

stationary use and can have the problem of obscuration. They are also known as SAR. The Spatial Reality Display reproduces spatial images in three dimensions as if they were real and can be viewed by the naked eye without special glasses or headsets (Figure 4).

Figure 4. Spatial Displays

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3. Collaborative robotics

The development of industrial automation during the last few decades has significantly changed the way production processes are organized. The introduction of industrial robots increased productivity, improved product quality and reduced the need for people to perform difficult and dangerous jobs. However, despite the rapid development of automation, human workers still play an irreplaceable role in many production activities. Humans have the ability to make decisions, adapt to unforeseen situations, think creatively and perform complex manipulative tasks, while robots provide great precision, speed, power and repeatability of work. Precisely because of the complementarity of their capabilities, the concept of human-robot collaboration (HRC) was developed, which represents one of the most significant trends within Industry 4.0 and 5.0. Instead of completely replacing human workers, modern production systems strive to achieve optimal cooperation between humans and robots in order to maximize the advantages of both participants in the work process. Collaborative robots, also known as cobots, represent a special category of industrial robots designed to work in close proximity to humans. Unlike traditional industrial robots that are mostly housed inside protective enclosures and physically separated from workers, collaborative robots can share the same workspace with

human operators. According to the ISO international standard, defines collaborative robots as robots designed for direct interaction with a human within a limited collaborative workspace. This approach enables a human and a robot to simultaneously perform different or interconnected tasks during the production process.

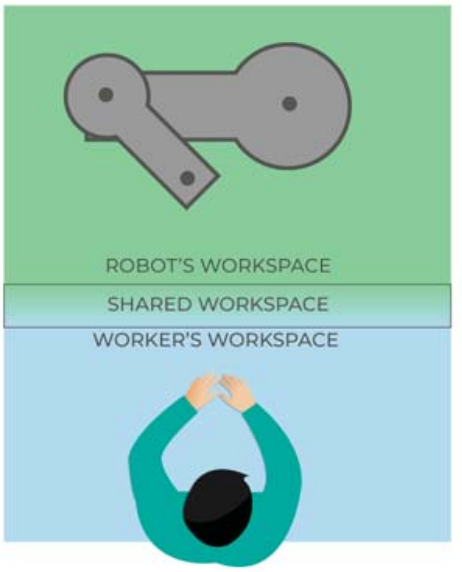

Figure 5 Workers' and robots' workspaces.

The basic idea of collaborative robotics is to combine human intelligence, flexibility and decision-making ability with the precision, strength and durability of robotic systems. In this way, it is possible to achieve higher productivity, better product quality and a safer working environment. Traditional industrial robots are primarily designed to perform repetitive tasks at high speed. Due to the large forces and movement speeds they develop, their use requires the installation of protective fences, safety sensors and other measures that prevent access by workers during robot operation. On the other hand, collaborative robots are designed with special safety functions that enable safe work near people (Figure 5). Their characteristics include:

- lower mass and more compact dimensions,
- limited speed and force of movement,
- built-in force and torque sensors,
- the possibility of detecting human contact,
- simple programming and configuration,
- greater flexibility when changing production tasks.

Thanks to these features, cobots can be relatively quickly integrated into existing production systems without the need for significant changes to the workspace. Safety is the most important aspect of the application of collaborative robots. Although it is often assumed that cobots are completely safe to work with humans, this assumption is not always true. A robot is not necessarily collaborative in itself, but a particular application becomes collaborative only after the implementation of appropriate safety features.

Figure 6 shows different types of cooperation between a human and an industrial robot, arranged according to the level of cooperation and safety requirements.

In the first case, called a cell, the robot works completely separately from the human within an enclosed space. There is a physical barrier that prevents any direct contact, so we cannot speak of real cooperation, but of classical automation. In coexistence, the robot and the human work in the same environment without a physical barrier, but they do not share the same workspace at the same time. Although they are close, their tasks are spatially separated, so the level of interaction is very low. Synchronization implies that the robot and the human use the same workspace, but not simultaneously. Their activities take place alternately, so that one completes its part of the task before the other begins. In cooperation, a robot and a human work simultaneously on the same task or part of the product. Both participants are active at the same time, which requires greater coordination and security measures. The highest level is responsive collaboration, where the robot reacts to human movements in real time. In this case, there is a direct and dynamic interaction, because the robot adjusts its behaviour in accordance with the operator's activities.

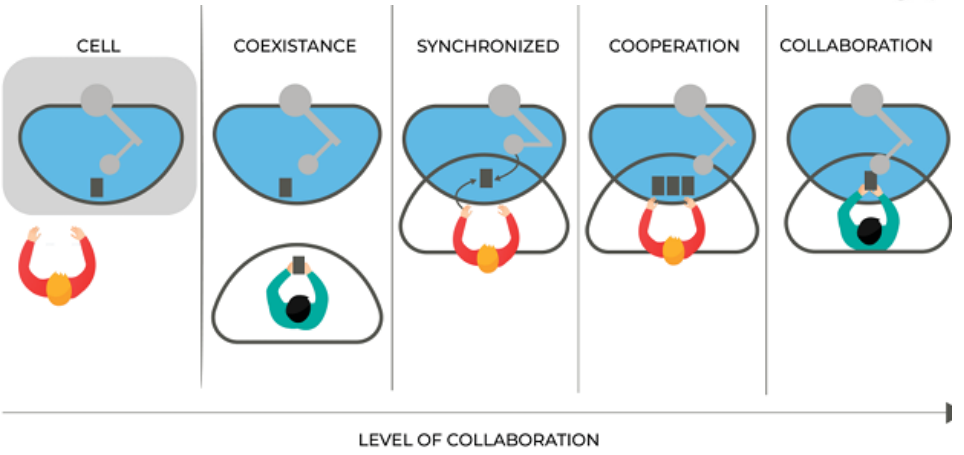

Figure 6. Levels of Interaction

Modern collaborative systems use different methods of operator protection. One of the most frequently applied methods is monitoring the speed and separation of man and robot. In this case, the sensors continuously monitor the distance between the operator and the robot and automatically reduce the speed or stop the robot when the human gets too close. The second method involves limiting the force and power of the robot. If there is contact between a human and a robot, the force developed remains within the permissible limits to avoid injuries.

However, safety also depends on the type of tool that the robot uses. For example, a robot equipped with a sharp tool, welding device or other dangerous attachment can pose a risk even when operating at low speeds. This is why a detailed risk assessment is necessary before implementing any collaborative system.

In recent years, the market for collaborative robots has seen extremely rapid growth. A large number of companies develop and produce cobots for various industrial applications. Among the most famous manufacturers are ABB, KUKA, Universal Robots, Yaskawa, COMAU, Franka Emika, TECHMAN Robot and Rethink Robotics. Each of these companies develops its own solutions adapted to the specific needs of users.

Universal Robots is considered one of the pioneers in the field of collaborative robotics and has significantly contributed to the popularization of cobots in small and medium-sized enterprises. ABB and KUKA develop advanced robotic systems for demanding industrial applications, while TECHMAN Robot integrates machine vision systems directly into robotic platforms. Franka Emika is especially known for flexible robotic solutions intended for research and advanced industrial applications.

Today, collaborative robots find application in almost all branches of industry. Their flexibility enables the performance of a large number of different tasks.

One of the most common applications of cobots is product assembly. Robots can precisely turn screws, place components and assemble products with minimal error. The operator performs more complex tasks and process monitoring, while the robot performs repetitive operations [8,9,10].

Collaborative robots are often used to apply adhesives, sealants, paints and other materials. Thanks to high precision, an equal amount of applied material and constant product quality are ensured. Grinding, polishing and surface treatment processes require precise and repeatable movements. Cobots can maintain a constant pressure force and processing speed, which achieves a uniform quality of the final surface.

In many factories, collaborative robots take over the tasks of loading and unloading parts from CNC machines, presses or plastic injection moulding machines. This increases the utilization of the equipment and reduces the burden on the operator. Packing, sorting, palletizing and transporting products are ideal tasks for cobots. Their ability to work in close proximity to people enables efficient organization of logistics processes within production facilities.

Collaborative robots can be equipped with cameras, sensors and machine vision systems that enable automatic product inspection. In this way, it is possible to detect errors in a timely manner and increase the quality of production.
Modern cobots are also used for various welding procedures. The robot ensures precise tool guidance and constant quality of the welded joint, while the operator monitors the process and makes adjustments as needed [11-15].
The use of collaborative robots brings numerous advantages to industrial companies. First of all, the productivity of production processes increases because the robot can continuously perform repetitive tasks without fatigue. At the same time, product quality improves thanks to high precision and repeatability of work.
An additional advantage is reflected in increased production flexibility. Unlike traditional automated systems, cobots can be reprogrammed for new tasks and products relatively easily. This is especially important for small and medium-sized enterprises that produce smaller series of products.
Collaborative robots also contribute to improving ergonomic working conditions because they take on physically demanding, monotonous and potentially dangerous tasks. In this way, the workload of workers is reduced and workplace safety is increased.
The further development of collaborative robots is closely related to the progress of artificial intelligence, machine learning, sensor technologies and machine vision systems. It is expected that future robots will be able to better understand human intentions, adapt their behaviour to changes in the environment and learn new tasks independently. Integration of cobots with Industry 4.0 technologies will enable even greater connectivity of production systems, real-time data exchange and optimization of production processes. In this way, human-robot cooperation will become one of the key elements of the smart factories of the future [16-20].

4. The Connection Between Augmented Reality (AR) and Collaborative Robotics

Augmented Reality (AR) and collaborative robotics represent two key technologies of modern industry that together contribute to increasing the productivity, safety and flexibility of production systems. Collaborative robots (cobots) are designed for safe work in close proximity to humans, while AR enables the display of digital information directly in the user's real environment. Their integration creates a more intuitive and efficient working environment [3].
One of the most important advantages of the integration of augmented reality (AR) and collaborative robotics is the visualization of information in real time. This capability allows operators to instantly obtain relevant data on the operation of the robot and the production process without the need to use additional monitors or control panels.
By using AR devices, such as smart glasses, tablets or mobile devices, digital information is displayed directly in a real work environment. The operator can see

the robot's position, movement speed, current task status, actuator load, safety zones and other process parameters at the time of their creation. In this way, an intuitive interaction between man and robot is realized.
Real-time visualization is especially important for collaborative robots because it enables a better understanding of their intentions and future movements. The AR system can display the planned path of the robot's movement before its execution, which reduces the possibility of collisions and increases the safety of the joint work of man and robot.

In production processes, operators can monitor:

- current status of task execution,
- positions and orientations of robotic tools,
- product quality parameters,
- warnings about errors and malfunctions,
- safety zones and areas of possible collision,
- data collected through sensors and IoT devices.

In addition to production, visualization of information in real time is also used during the maintenance of robotic systems. Technicians can instantly see diagnostic data, location of faulty components and recommended troubleshooting steps, significantly reducing system downtime.
Thanks to these possibilities, AR becomes an important tool for the improvement of collaborative robotics, because it increases the transparency of the process, accelerates decision-making, reduces the number of errors and contributes to safer and more efficient cooperation between humans and robots in the Industry 4.0 environment.
Simpler programming of robots with the use of augmented reality (AR) represents a modern approach to managing robotic systems in which complex programming code is replaced by intuitive interaction in real space (Figure 7). Instead of classical programming, the operator uses AR devices (eg smart glasses or a tablet) to define the robot's tasks directly in the physical environment. In the AR environment, the user can visually mark the robot's movement points, define paths, work zones and tool orientation simply by "pointing" or selecting objects in space. The system then automatically converts this information into a robot program. In this way, the need to manually write complex program instructions is eliminated. The key advantage of this approach is intuitiveness – the operator sees the real workspace alongside digital layers of information (eg the planned path of the robot, speed of movement or safety zones). This significantly reduces the probability of errors and speeds up the programming process.

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Figure 7. Robot programming using augmented reality

AR also enables visual simulation before execution, where the movement of the robot can be tested in real time without actually starting the machine (Figure 8). This increases security and enables quick corrections. In industrial environments, this way of programming is particularly useful in flexible manufacturing, where frequent task changes must be implemented quickly. Operators without advanced programming knowledge can efficiently adjust robots, which reduces dependence on specialized engineers. Augmented reality (AR) contributes significantly to increasing safety in industrial environments, especially in collaborative robotics systems where humans and robots work in the same workspace. AR allows operators to see in real time additional visual information that is not physically present, but is crucial for safe interaction with the system. One of the most important safety functions of AR is the visualization of safety zones around the robot. Using AR glasses or a tablet, the operator can see marked danger zones, robot reach limits and potential collision areas.

Figure 8. Simulations with the help of AR

In this way, the risk of accidental entry into the danger zone during machine operation is reduced.

Augmented reality (AR) significantly improves training and technical support processes in industrial environments, especially when working with collaborative robots and complex manufacturing systems. Instead of classic manuals and static instructions, AR enables interactive learning directly in the real workspace. In the training process, AR displays step-by-step instructions in real time, which are overlaid on the actual equipment. Trainees can see where certain parts of the robot are located, how to use them properly, and in what order to perform operations. This significantly reduces learning time and increases understanding of complex procedures.

AR also enables simulation of work without real risk, where users can practice programming, operating a robot or maintaining a system in a safe environment. In this way, the possibility of errors in real production is reduced.

5. Conclusion

Augmented reality and collaborative robotics represent complementary technologies that have significant potential for improving modern industrial production systems. While collaborative robots enable safe and efficient cooperation between humans and robots, augmented reality provides an intuitive way of displaying information, managing processes and interacting with the production environment. By integrating these technologies, greater transparency of production processes, simpler programming of robotic systems, more efficient

simulation of work operations, improved work safety and better training and technical support for operators is achieved. At the same time, productivity, production flexibility and product quality increase, while reducing the possibility of errors and downtime in the production process. Further development of artificial intelligence, machine vision, sensor technologies and the Internet of Things will further improve the possibilities of cooperation between humans and robots. It is expected that the integration of augmented reality and collaborative robotics will play an increasingly important role in the development of smart factories, where intelligent systems will enable more efficient, safer and more adaptable production processes in accordance with the requirements of Industry 4.0 and Industry 5.0.

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