Journal of Machine Engineering, 2025, Vol. 25
ISSN 1895-7595 (Print) ISSN 2391-8071 (Online)

Received: *11 February 2025* / Accepted: *07 April 2025* / Published online: *23 May*

Industry 5.0,
industrial robots,
humanoid robots,
smart manufacturing

Vjatsheslav KEKSHIN[1,2*], Sergei PONOMAR[1,2],
Martins SARKANS[2], Vladimir KUTS[2],
Sergei PAVLOV[1]

COLLABORATION BETWEEN INDUSTRIAL, COLLABORATIVE, HUMANOID ROBOTS AND HUMANS

One of the key aspects of Industrial Revolution 5.0 is the reintegration of humans into the industrial environment. This process enhances the interaction between various robots and humans in industry. This solves the problem of limiting the replacement of human resources in collaborative work with humanoid robots in production processes. The need for humanoid robots is particularly relevant in environments that are unsafe and pose significant health risks to humans. People with disabilities will be able to work effectively in environments where humanoid and collaborative robots are used. The scientific article explores the concept of Industry 5.0, focusing on the methodology for implementing and integrating technologies within the framework of smart manufacturing.

1. INTRODUCTION

Industrial transformation is a sociotechnical process. Industry 5.0 is one of the emerging terms describing this phenomenon. It is defined as a human-centered vision of technological transformations in industry, taking into account the current and future needs of workers and society while ensuring the sustainable optimization of energy consumption, material recycling, and product life cycles [1]. Within the framework of Industry 5.0, human interaction with industrial robotics becomes particularly significant. The use of various technologies, including the integration of human resources into Industry 5.0, offers numerous advantages. For example, it enhances workplace safety by reducing the risk of injuries for both employees and expensive equipment.

This scientific article focuses on analysing interactions between humans and humanoid robots, classifying these interactions, and applying them in research experiments. The

[1] Virumaa Innovation Centre of Digitalisation and Green Technologies, TalTech Virumaa College, Estonia[*]
[2] School of Engineering, Department of Mechanical and Industrial Engineering, Tallinn University of Technology, Estonia
E-mail: vjatseslav.keksin@taltech.ee
https://doi.org/10.36897/jme/203790

experiments are conducted in laboratory conditions using virtual reality, allowing test subjects to be immersed in a virtual manufacturing environment. This approach enables an objective assessment of the possibilities and effectiveness of human-robot interaction in an industrial setting.

The primary objective of this scientific article is to evaluate the potential for integrating and interacting with industrial and humanoid robots in manufacturing processes using virtual reality technologies. This approach allows for the identification of effective collaboration conditions, an increase in workplace safety, and the optimization of the implementation of robotic technologies in industry.

2. APPROACH

There are places in production where a person cannot work. For example, due to a hazardous environment, such as a strong magnetic field or a high concentration of air pollution caused by high dust levels. The use of humanoid robots has additional advantages, such as the ability to increase production. This allows for flexible adaptation of production capacities according to current needs, without the need to significantly increase the workforce. Humanoid robots can compensate for a shortage of labor or resources, as well as replace a human in case of their absence, which helps avoid production delays and financial losses. This helps eliminate costly production delays and protects the manufacturing process from significant financial losses. Figure 1 shows the main interactions between robots and humans: safety, communication, trust, integration, and usage limitations.

Fig. 1. Main interactions between Robot and Human

Safety – When working between robots and humans, it is essential to ensure the safety of both by preventing the robot from harming the human and protecting the robot from damage. The issue of assuring the safe operation of humanoid robots may well be one of the greatest challenges facing humanoid robot researchers [2]. Communication between different robots and humans – Effective communication is crucial in human-robot and robot-robot interactions to ensure all systems understand tasks and can make real-time decisions.

Decision-making layer involves the organization and allocation of system intent between the robot side and the human side. Collaborative human–machine decision-making is the core of human–machine cooperation, which is usually manifested in various control modes [3]. Trust between humans and robots – In collaborative work, actions must be well-coordinated, with confidence that the robot will not harm the human and clear responsibility assignment in case of issues. In general, trust attitude is considered to be one of the most important factors for successful collaboration [4]. Integration challenges – Integrating humans or robots into workflows requires time, expertise, and proper training for both sides. Through the integration of manufacturing and information communication technologies, AI-powered smart manufacturing systems can facilitate seamless communication, coordination, and collaboration between different parts of the manufacturing process, improving overall efficiency, quality, and productivity [5]. Usage limitations – This includes factors that restrict the interaction between robots and humans.

The implementation and integration of interactions between robots and humans provide numerous advantages, such as enabling quick selection, achieving practicality, and fostering the general integration of collaborative work or individual tasks. Traditional industrial robots pose a challenge to the integration of humanoid robots, as their use and availability have only recently begun to expand. The term "collaborative robot" is commonly known as Cobot, which refers to a partnership between a robot and a human [6]. Collaborative robots come equipped with safety features and do not require fences or other industrial safety equipment, further reducing costs and integration time [7]. A collaborative robot is inherently safe for humans. However, in some cases, the application that a collaborative robot can perform may not be safe for working alongside humans. Because of this, there is also a need to secure the workplace using special devices such as sensors, alarms, and additional enclosures around the hazardous work area. Humanoid robot is a robot in the shape of human which is designed to mimic the human body [8]. Previously, humanoid robots were accessible solely for laboratory research. Additionally, there are high requirements for the locations where these robots are planned to be used. Figure No. 2 shows the market segmentation in the field of humanoid robot development for the year 2023, representing the most up-to-date statistical data. This figure does not provide statistical information on the use of robots in the specified industries.

Fig. 2. Global Humanoid Robots Market Share, By Application, 2023 [9]

The large workforce of able-bodied individuals hinders the replacement of human resources with humanoid robots in production, verifying the relevance of this issue. However, there is a clear need for the use of humanoid robots in environments that are unsafe and pose significant health risks to humans. Additionally, people with disabilities can work more efficiently in such environments through the integration of humanoid and collaborative robots.

Some of the devices for human interaction with Industry 5.0, which include humanoid robots and industrial robots, are the smart exoskeleton and eye tracking. Eye-tracking allows researchers insight into behaviour with minimal interruption and into periods when the users are not aware of their own behaviour [10]. Currently, there are numerous devices available for using EYE Tracking Lab, with brands from various manufacturers [11]. Although eye-tracking is not directly used in our research, it plays an important role in evaluating human interaction with robotic systems. Including a description of eye-tracking helps provide a better understanding of users' subjective experiences during interaction with robots. This is a crucial part of the study, as it allows for the analysis of participants' attention and focus on specific aspects of the robot or its actions. Additionally, it provides valuable data for assessing the efficiency and comfort of using robotic systems in various conditions. The smart exoskeleton enhances human capabilities by reducing strain on muscles, joints, and other body parts involved in lifting and carrying heavy loads. Exoskeletons are predominantly used pre-emptively in production to enhance the actual ergonomic work situation of the workers [12]. Unlike a simple exoskeleton, the smart exoskeleton allows data collection during use, enabling statistical analysis of total working time and overall weight lifted. Additionally, predictive maintenance for the exoskeleton helps identify malfunctions in time, notifying users about breakdowns. The sensors installed on the exoskeleton, used to record the user's movements, can provide data for programming tasks for humanoid robots.

The lack of engineering resources for integrating and configuring humanoid robots into production processes creates significant challenges. Furthermore, limited information about modern working conditions perpetuates misconceptions that production environments are unfavourable, making it harder to attract employees. Many workplaces involve physically demanding and monotonous tasks, which negatively impact workers' health and well-being. This, in turn, leads to production defects, temporary delays, and errors, highlighting the critical need for improved working conditions and advanced automation solutions like humanoid robots.

If the problem is solved, it will enable the widespread use of humanoid robots alongside industrial robots and humans, with designated areas for their interaction and areas where interaction is restricted or excluded from production processes. However, if the problem remains unresolved, integrating humanoid robots with industrial robots and humans will be challenging, hindering their widespread adoption and slowing the development of production processes.

3. MATERIALS AND METHODS

The method for evaluating the integration using virtual reality of human interaction with industrial and humanoid robots in the collaborative execution of work tasks in production. In a safe virtual reality environment, separate from production, the tested entity demonstrates its ability to interact with collaborative robotic production technologies, such as industrial robots and humanoid robots.

The method allows for the development of a workflow scenario that defines areas of possible joint participation of humanoid robots together with humans working in production. The use of humanoid robots instead of collaborative robots in VR tests is due to the fact that the application of humanoid robots in production for collaborative work with humans is still less studied compared to collaborative robots. This, in turn, is closely related to the social interaction between humanoid robots and humans. In Figure 3, the Layout of Visual Components and AC Outdoor Unit Assembly. Visual Components stands out as a dominant player in the realm of engineering software, particularly in modelling 3D layouts and simulating industrial processes [13].

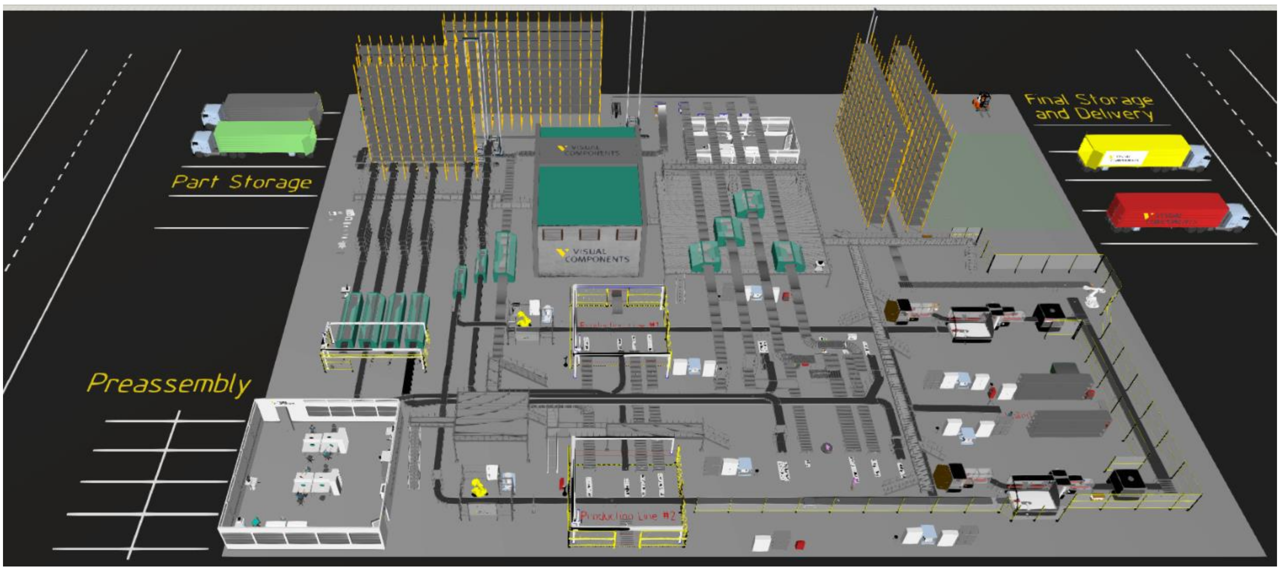

Fig. 3. The Layout of Visual Components and AC Outdoor Unit Assembly [14]

We immerse the test subject in the layout "The Layout of Visual Components and AC Outdoor Unit Assembly" using the 3D simulation program Visual Components with the help of virtual reality glasses (VR). Virtual Reality (VR) is a three-dimensional digital environment which allows multiple degrees of freedom for the user to interact with the environment and engage in immersive interactions [15]. The layout features a large-scale production facility, as it contains a significant amount of equipment and a multifunctional technological process. This implies the use of extensive human resources, which can generally be divided into several groups: operators working with technological equipment and engineering personnel responsible for setup and commissioning of all technological equipment in smart manufactory. In addition, today's smart manufacturing integrates machines and humans. These benefits of smart manufacturing result in the cost-effective use of manufacturing resources and a reduction in the time to market [16]. During the testing, the subjects familiarize themselves with the workplace in the virtual production environment and identify areas in their work environment where a humanoid robot could partially replace a human or, if necessary, take over the entire work shift of a worker in the production environment. In the event of an emergency situation, a humanoid robot can be deployed to unload the production line or conveyor to prepare the production area for restart. We initiate an emergency situation in which the operator shuts down the line by pressing a button in the virtual environment. Then, it is necessary to unload the jammed line and reactivate it from the operator's control panel. This allows the operator to learn or train on the actions they need to take in their work. During this type of simulation, the time and movements of the test subject are recorded, which provides information on how to program the humanoid robot for this type of emergency scenario. The collected data, when analyzed, helps in creating the main configuration and setup of the humanoid robot.

The experiment was conducted at TalTech Virumaa College, in the city of Kohtla-Järve, at the Virtual Reality Laboratory, Fig. 4. The primary goal of the experiment was to determine the interaction between participants and a humanoid robot in a production environment using virtual reality.

Fig. 4. Test Subjects Using Virtual Reality and the Layout Program Visual Components

A total of 16 participants took part in the experiment. The participants were from different backgrounds: professionals with extensive experience in industrial enterprises and young students with little or no experience in the field of production. Before the experiment, participants underwent a brief training session and were introduced to the experiment guidelines, providing written consent for their participation. The experiment guidelines contained essential introductory information, including: Description of the Experiment – The aim of the experiment is to immerse the subject in a virtual environment where a production process is simulated, studying the ability of a humanoid robot to collaborate with a human in various situations. The main interactions analyzed include safety, communication between robots and humans, trust, integration challenges, and usage limitations. The experiment takes place today at the TalTech Virumaa College Virtual Reality Laboratory in Kohtla-Järve on 10.02.2024. What data is collected? – Data is gathered through objective evaluation, including surveys and interviews conducted before, during, and after the experiment. Additionally, behavioral reactions such as reaction time and decision-making are recorded. A stopwatch measures adaptation to using VR devices, adaptation to the Visual Components Layout environment, and task completion in these environments. What are the risks of the experiment for the participant? Participants with epilepsy may experience worsening symptoms, making VR testing contraindicated. If mild dizziness occurs during the test, it must be stopped immediately. Sharp movements and leaving the test area are prohibited to prevent injuries. In case of any discomfort, the participant should notify the supervisor immediately. After each test, VR glasses and controllers are disinfected with a special solution and wiped clean. How is the data processed? The instructor records and manually enters the data onto paper, after which the subject reviews and confirms it with their signature. Joint signatures of the subject and the instructor verify the manually entered data.

The first step of the experiment involved introducing participants to VR headsets, learning how to use them, and practicing working with controllers, which allow various manipulations in the virtual reality environment. The second step consisted of a brief introduction to production using VR technology, where the participant conducted an independent overview of the Layout (Fig. 3). The third step required participants to observe a humanoid robot performing a work task near them and in the general workspace. This step involved direct interaction between the participant and the humanoid robot in a collaborative work scenario, addressing key aspects of human-robot interaction, including safety, communication, trust, integration, and usage limitations. This practical experience provided participants with a deeper understanding of these aspects, enabling them to consciously respond to the questions posed in Table 1. Based on the data obtained from 16 participants, several key conclusions can be drawn. The majority of participants (15 out of 16) feel safe using virtual reality glasses and in the Virtual Components production line virtual environment, while 14 participants feel safe in a real production environment and 15 feel safe working next to humanoid robots. However, 2 participants do not feel safe in a real environment, and 5 participants believe that robots could replace their work in the short-term or long-term production process. Regarding communication, 12 participants support the possibility of communicating with robots via voice and gestures, while 15 participants agree with the possibility of using these methods separately. Additionally, most participants (15 out of 16) support the possibility of communicating with robots via other methods. All participants trust virtual reality technology for preparing to collaborate with humanoid robots, and they trust other people working with such robots. 15 participants are confident that humanoid robots can perform tasks with high quality, but only 9 participants believe that robots trust collaborating with them. Regarding integration issues, opinions are divided: 8 participants believe that integrating humanoid robots into a shared work environment with their involvement is difficult, while 10 believe that integrating robots when working with other people is challenging. Furthermore, 9 participants find it difficult to integrate robots into an environment without human involvement. 15 participants agree that humanoid robots have usage restrictions in the production environment, while 7 participants think robots limit workers' tasks or the work environment, and 10 believe robots limit social interactions. Regarding participants' experience, 7 have experience working with virtual reality technologies, 6 have experience working in production, and only 3 have experience working with industrial or humanoid robots. Most participants (11 out of 16) believe they are capable of performing tasks that humanoid robots can do. These results provide valuable insights into the perception of safety, communication, trust, integration issues, and the potential impact of humanoid robots in a production environment.

Table. 1. Questionnaire for the experiment participant

	1. Safety	Yes	No
1.	Do you feel safe using virtual reality glasses?	15	1
2.	Do you feel safe in the Visual Components production line virtual environment?	16	
3.	Would you feel safe in a similar production environment, but real, not virtual?	14	2
4.	Do you feel safe working next to a humanoid robot?	15	1
5.	Do you think a robot can replace your work in the short-term or long-term production process?	11	5
	2. Communication between robots and humans	Yes	No
1.	Do you allow the possibility of communicating with a robot in the production process via voice and gestures?	12	4
2.	Do you allow the possibility of communicating with a robot in the production process via voice?	15	1
3.	Do you allow the possibility of communicating with a robot in the production process via gestures?	15	1
4.	Do you allow the possibility of communicating with a robot in the production process via some other communication method?	15	1
	3. Trust between humans and robots	Yes	No
1.	Do you trust virtual reality technology to explore and prepare for your collaboration with humanoid robots in production?	16	
2.	Do you trust other people to work with humanoid robots in production?	16	
3.	Do you trust that a humanoid robot can complete the task assigned to it with high quality?	15	1
4.	How do you think a humanoid robot would trust collaborating with you?	9	5
	4. Integration issues	Yes	No
1.	How do you think, is it difficult to integrate a humanoid robot into a shared work environment with you?	8	8
2.	How do you think, is it difficult to integrate a humanoid robot into a shared work environment with other people?	10	6
3.	How do you think, is it difficult to integrate a humanoid robot into a shared work environment without the involvement of humans?	9	7
4.	How do you think, is it difficult to integrate a humanoid robot into a work environment with different circles of human interaction?	11	5
	5. Usage restrictions	Yes	No
1.	Do humanoid robots have restrictions on use in the production environment?	15	1
2.	Does a humanoid robot limit the work of people when they are working with the robot in production?	7	9
3.	Does a humanoid robot limit the work environment in the company?	7	9
4.	Does a humanoid robot limit social interaction between people in the company?	10	6
	6. Other questions	Yes	No
1.	Do you have experience working with VR technologies?	7	9
2.	Do you have experience working in production?	6	9
3.	Do you have experience working with industrial robots or humanoid robots?	3	12
4.	Are you capable of performing the exact same tasks as humanoid robots?	11	4

Each stage of the experiment was measured with a stopwatch for every participant, and the recorded data was entered into the time registration tables (Table 2). These tables included three primary time measurements: adjusting time for VR device usage, adjusting time for location determination in the Visual Components environment, and the impact of task assignment in the VR environment and the Visual Components layout. These data points help determine the speed of participant adaptation, demonstrating that the adaptation process occurs quickly. This suggests that participants develop a clear understanding and motivation, which enables them to provide high-quality answers to the questions in Tab. The last two columns of the table contain the number of responses to each question from all 16 participants. These data provide insights into how humanoid robots are perceived in a shared work environment, forming the basis for analysing or refining their use in collaborative work processes. Two participants refrained from answering a specific question in Section 3: Trust between humans and robots, specifically question 4: "How do you think, is it difficult to integrate a humanoid robot into a work environment with different circles of human interaction?" This suggests that they do not consider it possible for a humanoid robot to independently select or regulate human involvement in its workflow. However, the majority of participants accepted the idea that a humanoid robot could perform such actions.

As the author of this study, I believe that in certain cases, such a function could be permitted for humanoid robots. A humanoid robot could regulate access to work tasks in its production area, allowing only qualified individuals to perform specific jobs. If an unqualified individual attempts to access a task, the robot could signal this by sending a notification to the production manager or issuing an audio alert.

Based on the data (Table 2) obtained from the participants, several key observations can be made. The task completion times vary significantly, ranging from a few seconds (for example, 5 seconds for participant 2 in column O) to several minutes (for example, 6 minutes for the same participant in column J). In some cases, there is a substantial variation in the time taken to complete the same task by different participants, which may indicate differences in task complexity or individual characteristics of the participants. Repeated values were also identified. For example, for participant 3, the completion time is consistently 1:30 in most cases, which may indicate either the stability of their performance or the nature of the tasks being performed. Additionally, the value 1:37 appears for several participants, which may suggest a standard completion time for a particular type of task.

Table. 2. Adaptation Measurement of Participants to New Equipment and Test Tasks – 1. Adjusting time for VR device usage – 2. Adjusting time for location determination in the Visual Components environment – 3. The impact of task assignment in the VR environment and the Visual Components layout

Participant	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P
1	25 s	30 s	1:37	30 s	26 s	1:37	1:06	0	1:56	1:53	1:37	20 s	2:50	53 s	0	20 s
2	1:00	20 s	1:35	1:00	10 s	1:25	1:00	2:00	2:30	6:00	1:00	37 s	1:00	1:00	5 s	35 s
3	2:50	1:30	1:30	1:30	1:30	1:30	1:30	1:30	1:30	1:30	1:28	1:30	1:30	1:30	1:05	2:50

There are zero values observed for participants 1 and 2 in certain columns (for example, H1, P1, O2), which could indicate non-completion of tasks, technical issues, or omissions. When comparing the average results, it is clear that participant 3 shows the most stable performance, while participant 2 demonstrates the greatest variability in task completion time, which may indicate different adaptation speeds to the tasks. Based on this data, several conclusions can be drawn. The variation in completion times may be related to differences in task complexity or individual characteristics of the participants. Repeated values may indicate standardization of certain task stages. Zero values require clarification regarding their causes, whether it is non-completion of tasks or technical errors. For more detailed analysis, the average completion time, median, and standard deviation can be calculated, which will help identify additional patterns.

5. CONCLUSION

During the study, the set objectives were accomplished by assessing the readiness of test subjects for various work scenarios in a manufacturing environment while interacting with industrial and humanoid robots. Specific areas in production were identified where humans can collaborate with humanoid robots. This method allows for the assessment of the feasibility of integrating industrial and humanoid robots into existing manufacturing processes using virtual reality. While VR aligned somewhat with results of traditional methods, especially in representing perceived security, further refinement is needed to ensure that all key attributes are effectively captured across different methods [17]. The developed work scenarios can optimize production processes and reduce integration time. When selecting and installing a robot type, such as a humanoid robot or an industrial collaborative robot, it is important to consider that if the work is repetitive and requires the robot to remain in a fixed workstation, an industrial collaborative robot should be used in this case. As a result of this study, the effectiveness and potential of human-robot interaction in production environments were carefully assessed. The use of virtual reality allowed for an immersive and objective evaluation of how humans can interact with industrial and humanoid robots in simulated industrial environments. The results revealed key factors that contribute to effective collaboration, including the identification of optimal working conditions and safety standards. It was also demonstrated how virtual reality can be used to optimize the integration of robotic technologies into existing production processes, ultimately contributing to improved efficiency, safety, and productivity in industry.

ACKNOWLEDGEMENTS

This article thesis was supported by the project "Increasing the knowledge intensity of Ida-Viru entrepreneurship" co-funded by the European Union (IKRA-T5.0 – Development of process-adaptable robot platforms in the Industry 5.0 concept (incl. digital twin)).

REFERENCES

[1] BARATA J., KAYSER I., 2023, *Industry 5.0 – Past, Present, and Near Future*, Procedia Computer Science, 778–788, https://doi.org/10.1016/j.procs.2023.01.351.

[2] GRAHAM J.H., 2000, *Safety Considerations for Humanoid Robots*, IEEE-RAS International Conference on Humanoid Robots, 1–8, http://humanoids.cs.tum.edu/25.pdf.

[3] YANG C., WU X., LIN M., LIN R., WU D., 2024, *A Review of Advances in Underwater Humanoid Robots for Human–Machine Cooperation*, Robotics and Autonomous Systems, 104744, https://doi.org/10.1016/j.robot.2024.104744.

[4] ROESLER E., VOLLMANN M., MANZEY D., ONNASCH L., 2024, *The Dynamics of Human Robot Trust Attitude and Behavior – Exploring the Effects of Anthropomorphism and Type of Failure*, Computers in Human Behavior, 108008, https://doi.org/10.1016/j.chb.2023.108008.

[5] WAN J., LI X., DAI H.N., KUSIAK A., MARTINEZ-GARCIA M., LI D., 2021, *Artificial-Intelligence-Driven Customized Manufacturing Factory: Key Technologies, Applications, and Challenges*, Proceedings of the IEEE, 377–398, https://doi.org/10.1109/JPROC.2020.3034808.

[6] JAVAID M., HALEEM A., SINGH R.P., RAB S., SUMAN R., 2022, *Significant Applications of Cobots in the Field of Manufacturing*, Cognitive Robotics, 222–233, https://doi.org/10.1016/j.cogr.2022.10.001.

[7] ANANIAS E., GASPAR P.D., 2022, *A Low-Cost Collaborative Robot for Science and Education Purposes to Foster the Industry 4.0 Implementation*, Appl. Syst. Innov., 5, 72, https://doi.org/10.3390/asi5040072.

[8] FAREH R., KHADRAOUI S., ABDALLAH M.Y., BAZIYAD M., BETTAYEB M., 2021, *Active Disturbance Rejection Control for Robotic Systems: a Review*, Mechatronics, 102671, https://doi.org/10.1016/j.mechatronics.2021.102671.

[9] Web page, 2024, *Main Interactions Between Robot and Human*, www.fortunebusinessinsights.com.

[10] KOFFSKEY C.M., 2014, *Using Eye-Tracking to Investigate Strategy and Performance of Expert and Novice Control Room Operators*, Louisiana State University, LSU Master's Theses, 3353, https://doi.org/10.31390/gradschool_theses.3353.

[11] KEKSHIN V., KUTS V., DERBNEV M., SARKANS M., 2024, *Review of Possibilities in the EYE-TRACKING LAB for the Safety of Process Control Operators*, Safety of Industrial Automated Systems, 1–5, https://www.automaatioseura.fi/site/assets/files/4501/sias_2024_paper_46.pdf.

[12] DAHMEN C., WÖLLECKE F., CONSTANTINESCU C., 2018, *Challenges and Possible Solutions for Enhancing the Workplaces of the Future by Integrating Smart and Adaptive Exoskeletons*, Procedia CIRP, 268–273, https://doi.org/10.1016/j.procir.2017.12.211.

[13] KEKSHIN V., SARKANS M., KUTS V., 2024, *Developing of an Engineering Scientific Innovative Lab and Teaching Methodology for Smart Manufacturing in the Hi-Engineering School*, ASME 2024 International Mechanical Engineering Congress and Exposition, 143105, V002T03A073, 8, https://doi.org/10.1115/IMECE2024-143105.

[14] Visual Components software, 2024, *Ac Outdoor Unit Assembly*, Visual Components Premium 4.8.

[15] LAMB R., 2023, *Virtual Reality and Science, Technology, Engineering, and Mathematics Education*, International Encyclopedia of Education (Fourth Edition), 189–197, https://doi.org/10.1016/B978-0-12-818630-5.13075-1.

[16] BARARI A., TSUZUKI M.S.G., 2023, *Smart Manufacturing and Industry 4.0*, Appl. Sci., 13, 1545, https://doi.org/10.3390/app13031545.

[17] FACCHINI G., LARRANAGA A.M., CANDIDO DOS SANTOS F.A., DOS SANTOS, CHRISTINE TESSELE NODARI M.L., GARCIA D.S.P., 2025, *Virtual Reality in Stated Preference Survey for Walkability Assessment*, Transportation Research Part D: Transport and Environment, 104545, https://doi.org/10.1016/j.trd.2024.104545.