

**XR технологии и виртуални лаборатории в обучението  
по индустриална роботика: обзор и практическа реализация**  
Александър Иванов, Павел Златаров, Юксел Алиев, Галина Иванова

**XR Technologies and Virtual Laboratories in Industrial Robotics Education:  
Overview and Practical Implementation**

Aleksandar Ivanov, Pavel Zlatarov, Yuksel Aliev, Galina Ivanova

**Abstract:**

The paper examines the role of virtual and augmented reality (XR) technologies as a key element of the digital transformation of industrial robotics education. An overview of contemporary approaches to building virtual laboratory environments is presented, including the use of interactive 3D simulations, digital twins, and specialized educational platforms that enable the safe and accessible acquisition of practical skills. The main advantages of XR-based solutions are analyzed, such as improved visualization of complex processes, reduced risk when working with real equipment, and expansion of opportunities for independent learning. The possibility for the application of an XR-based laboratory environment using the zSpace system and specialized software for industrial robotics training is described, with a perspective for integration with industrial simulation software and a real robotic arm. The main challenges in implementing such technologies are presented, as well as the possibilities for future research related to evaluating their effectiveness and expanding their application in engineering education.

**Keywords:** XR technologies, virtual laboratories, industrial robotics, engineering education, robot simulation

**For contacts:** Aleksandar Ivanov, University of Ruse, akivanov@uni-ruse.bg

**INTRODUCTION**

In modern manufacturing, industrial robotics play an increasingly important role as a key part of contemporary automated production systems [1, 2]. The increasing adoption of Industry 4.0 technology and emergence of smart factories has created a high demand for engineers possessing theoretical and practical knowledge of robotic systems and industrial automation [3]. All of this has made industrial robotics education an essential part of engineering programs in areas such as automation, mechanical engineering, mechatronics, and even computer engineering [3].

A significant number of challenges have limited the effectiveness of traditional, laboratory-based training, which has long been an essential element of engineering education [4]. Industrial robotic systems have long been associated with significant financial investments and strict maintenance requirements [4]. Student access to real robotic equipment might also introduce certain safety concerns, as well as the risk of equipment damage and costly repairs; additionally, due to resource limitations, time spent with laboratory equipment by each student might be severely limited, and even with proper access, future engineers might still have difficulty understanding and visualizing complex robot movements, kinematics, and interactions, due to the complexity of the majority of such systems [4].

In recent years XR (extended reality) technologies have emerged as a promising approach for augmenting engineering education, and supporting practical training in technical subjects [5, 6]. Virtual, augmented and mixed reality environments have the potential to facilitate visualization of complex processes, encourage safe

experimentation without the need for students to interact with real industrial equipment until they have acquired the necessary knowledge and expertise to do so [5, 6]. Thus, XR has significant potential to aid in the gradual transition from theoretical preparation to simulation activities and real-world practice.

## **XR TECHNOLOGIES AND VIRTUAL LABORATORIES IN INDUSTRIAL ROBOTICS EDUCATION**

Virtual laboratories can be defined as software-based environments (often combined with relevant hardware) that simulate or provide remote access to real, physical laboratory systems [4]. These environments can enable students to carry out practical tasks, to experiment and even simulate complex processes in a controlled, safe environment. Virtual laboratory environments have long been used in engineering education to improve accessibility, encourage independent learning, and overcome the limitation associated with physical laboratory infrastructure [4].

Extended reality (XR) is a collective term that describes visual immersive technologies such as Virtual Reality (VR), Augmented Reality (AR) and Mixed Reality (MR). While these technologies look similar on the surface, there are a few important differences [5, 6]:

- Virtual reality is designed to create a fully digital, immersive environment, fully separated from the real world;
- Augmented reality uses the real-world environment and overlays digital elements;
- Mixed reality combines elements from VR and AR, and allows interaction between immersive environments and real-world elements.

In educational environments, XR technology can be used to enhance visualization, provide improved interactivity, and boost practical engagement during the learning process [5, 6].

Applying XR technology in the context of industrial robotics education has a few important advantages. First, the use of interactive 3D visualization helps students better understand the structure, movements, and operational principles of industrial robots [7]. Additionally, XR environments encourage the “learning by doing” approach, which increases learner engagement and active participation [5, 6]. Finally, they enable the repeatability of training exercises, while reducing or eliminating the risks associated with equipment damage or operator safety [7, 8, 9]. If students possess the appropriate equipment (VR headset, stereoscopic display, among others), the technology can also provide opportunities for remote and independent learning activities [8].

## **METHODOLOGY AND PRACTICAL IMPLEMENTATION**

The identified limitations of industrial robotics education, together with the capabilities provided by XR technologies, motivated the proposition of a training methodology that integrates theoretical instruction, immersive XR environments, robotic simulation, and practical work with real industrial robotic systems. The proposed approach combines theoretical instruction with XR-enhanced learning, while allowing for the transition to simulation environments and real industrial robotic systems. An overview of the proposed methodology is shown on Fig. 1.

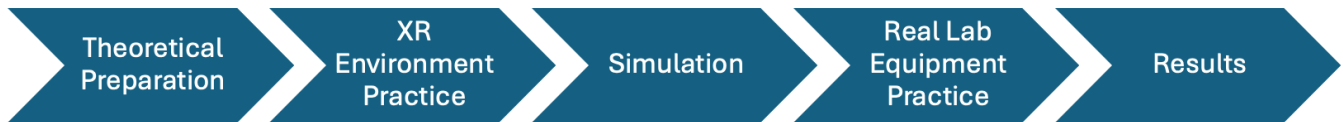


Fig. 1 Overview of the proposed methodology

Students begin with theoretical preparation (lectures) about the structure of robotic systems, their kinematics, and basic industrial automation concepts; they then transition to practical exercises in an XR environment, which use 3D visualization tools to improve understanding of robotic operations and movements, building on the knowledge acquired during the theoretical preparation. In addition to understanding the equipment's structure, XR tools can be used to simulate entire production workflows and maintenance processes associated with industrial robots.

After completing the XR-based activities, educators and students can opt to move on to simulation-oriented training, using specialized industrial robotics software. Simulated environments allow testing of robotic movements, program execution and process validation before interacting with real laboratory or industrial equipment. This approach has the potential to enable a smoother and safer transition from virtual environments to real robotic systems, as students have the option to see how their programs function or control simulated robots and see how they behave, without the safety implications that this might produce in a real environment [9, 10].

A practical implementation of the proposed approach can be achieved using platforms such as zSpace Inspire 2 and specialized software packages for industrial robotics training. The zSpace system is capable of stereoscopic 3D visualization, and supports interaction via traditional peripherals (e.g. mouse and keyboard), or via a dedicated stylus device [11]. The latter provides a more interactive, hands-on experience, and enables students to interact with virtual robotic systems in an immersive environment. Software packages that are usable in an industrial robotics-related education environment include:

- Industrial Robotics Training (AP182), which can be useful in introducing students to the foundations of industrial robotics, and showcases the structure and operation of the mechanical, electrical, pneumatic, hydraulic, control, and vision systems used in modern industrial robots [12].
- Industrial Robotics Operations (AP184) provides a virtualized version of real-world industrial environment workstations, including welding and spray-painting stations [12]. In addition to operating the industrial robots used in these stations, students are able to simulate most parts of the manufacturing process, such as preparation and shutdown procedures, tool usage, programming, and safety protocols.
- Industrial Robotics Maintenance (AP183) aims to introduce students to maintenance procedures, assembly, inspections and adjustments that can be made to robotic motion and electrical systems, among others [12, 13].

Fig. 2 shows the use of Industrial Robotics Training (AP182) in a classroom environment, using zSpace Inspire 2. The system is portable, allowing students to work independently, and can even be used in laboratories where real robotic equipment is

present, should the need arise for students to refresh their memory on the procedures and protocols showcased by the system.

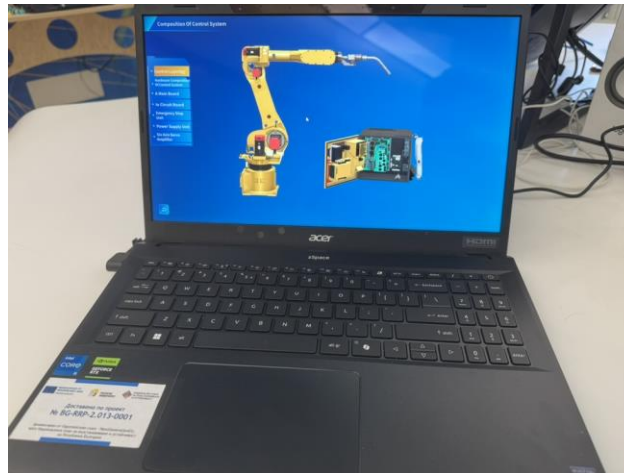


Fig. 2 Use of Industrial Robotics Training in a classroom environment with zSpace Inspire 2

XR environments, while powerful in helping students take their first steps in robotics, can be severely limiting, as they may be largely confined to predefined training activities and simplified versions of scenarios. As such, these activities can be combined with specialized simulation software platforms that are standardized in the robotics industry. These systems allow for the creation and testing of fully capable robotic cells and manufacturing workstations, real-time visualization of robotic movements, and validation of production scenarios, before moving on to real equipment. Software packages, such as ROBOGUIDE, provide more advanced functionality compared to the XR solutions, but, while steps are being made by their developers to support XR environments, can be less immersive [14]. Thus, the combination of XR technology and industrial simulation software has the potential to facilitate a more comprehensive educational process, and aid in the transition from theory to practice with real robotic systems. An example of a simple educational robotic cell, simulated using FANUC ROBOGUIDE, is shown on Fig. 3. In this example, the software simulates all parts of the system, including the robotic arm, controller, teach pendant, and runs a real program as it would run on a real system [14].

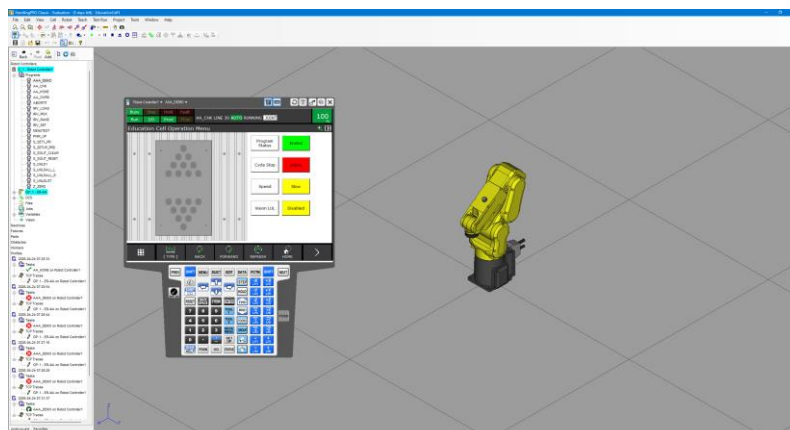


Fig. 3 Simulation of an industrial robot cell in ROBOGUIDE

## CHALLENGES AND FUTURE DIRECTIONS

While XR technologies provide various advantages, they also introduce several important challenges related to their implementation in engineering education. One of

the more significant limitations is the high initial cost associated with specialized hardware and software platforms [5, 6]. Other challenges can also arise, including the need for curriculum adaptation, instructor training and integration with existing laboratory infrastructure, most of which is often proprietary. Additionally, while XR environments can be comprehensive, they are not always able to reproduce all conditions and constraints present in real industrial systems.

Future research is expected to focus on evaluating the educational effectiveness of XR-based training approaches, compared to traditional methods. Development opportunities include tighter integration with simulation software, expansion of virtual laboratory functionality (including exploring possibilities for remote access), and exploring the application of the approach in other engineering disciplines. More advanced implementations may explore the usage of AI-assisted tools within XR-based and simulated learning environments.

## **CONCLUSION**

XR technology can significantly expand the possibilities for safer and more interactive education of engineers in industrial robotics. Virtual laboratories and simulation platforms support the understanding of complex processes and protocols in industrial robotics, and can improve student preparation before practical work with real systems. While XR cannot fully replace traditional laboratory activities, they can offer an effective complementary approach that enables a smoother transition from theoretical learning to practical training.

## **ACKNOWLEDGEMENTS**

This study is financed by the European Union-NextGenerationEU, through the National Recovery and Resilience Plan of the Republic of Bulgaria, project No. BG-RRP-2.013-0001-C01.

## **REFERENCES**

1. Müller, C. (2024). World robotics 2024: Industrial robots: Executive summary. International Federation of Robotics. Retrieved April 2026, from [https://ifr.org/img/worldrobotics/Executive\\_Summary\\_WR\\_2024\\_Industrial\\_Robots.pdf](https://ifr.org/img/worldrobotics/Executive_Summary_WR_2024_Industrial_Robots.pdf)
2. De Backer, K., DeStefano, T., Menon, C., & Suh, J. R. (2018). Industrial robotics and the global organisation of production (OECD Science, Technology and Industry Working Papers No. 2018/03). OECD Publishing.
3. Quintero, W. R., & Maldonado, J. E. N. (2024). Competencies of the engineer in industry 4.0 context: a systematic literature review. *Production*, 34, e20230051.
4. Potkonjak, V., Gardner, M., Callaghan, V., Mattila, P., Guetl, C., Petrović, V. M., & Jovanović, K. (2016). Virtual laboratories for education in science, technology, and engineering: A review. *Computers & Education*, 95, 309-327.
5. Burke, D., Crompton, H., & Nickel, C. (2025). The use of extended reality (XR) in higher education: A systematic review. *TechTrends*, 69, 998–1011. <https://doi.org/10.1007/s11528-025-01092-y>
6. Huang, T. C., & Tseng, H. P. (2025). Extended reality in applied sciences education: A systematic review. *Applied Sciences*, 15(7), 4038.

7. Mulero-Pérez, D., Zambrano-Serrano, B., Ruiz Zúñiga, E., Fernandez-Vega, M., & Garcia-Rodriguez, J. (2025). Enhancing Robotics Education Through XR Simulation: Insights from the X-RAPT Training Framework. *Applied Sciences*, 15(18), 10020.

8. Tzafestas, C. S., Palaiologou, N., & Alifragis, M. (2006). Virtual and remote robotic laboratory: Comparative experimental evaluation. *IEEE Transactions on education*, 49(3), 360-369.

9. Hönig, W., Tavakoli, A., & Ayanian, N. (2016). Seamless robot simulation integration for education: a case study. In *Workshop on the role of simulation in robot programming at SIMPAR*.

10. International Organization for Standardization. (2025). ISO 10218-1:2025: Robotics: Safety requirements: Part 1: Industrial robots. Retrieved April 2026, from <https://www.iso.org/standard/73933.html>

11. zSpace. (2024). Inspire, Inspire 2, and Inspire 2 Pro editions: Technical specifications. Retrieved April 2026, from <https://cdn.zspace.com/downloads/documentation/specifications/zSpace-Inspire-inspire2-inspire2pro-TechSpecs.pdf>

12. VR Expert. (2026). zSpace robotics solution. Retrieved April 2026, from <https://vr-expert.com/zspace/zspace-robotics-solution/>

13. zSpace Support. (2025). Industrial robotics maintenance by zSpace. Retrieved April 2026, from <https://support.zspace.com/s/article/Industrial-Robotics-Maintenance-by-zSpace>

14. FANUC Corporation. (2025). ROBOGUIDE: Robot system design tool. Retrieved April 2026, from <https://www.fanuc.co.jp/en/product/catalog/pdf/robot/ROBOGUIDE%28E%29-13.pdf>