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A workflow for extended reality-based learning in engineering education

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ABSTRACT

The integration of advanced extended reality technologies in the manufacturing and industrial context through the evolution of Industry 4.0 to the more user-centric Industry 5.0 paradigm guides the transformation of how end users access and control cyber-physical systems and real-time data sources. This is applicable both in real-world manufacturing contexts and higher education institutions, where future engineers learn how to design and manage these production systems. Extended reality (XR) has become an integral part of several aspects of industrial human-machine interaction methods, including diagnostic data visualization, teleoperation, augmented servicing and assembly instruction procedures, and safe operation of heavier machinery. In the educational context, XR allows for hands-on virtual activities, repeatability, and extended accessibility of limited resources before laboratory practical tasks. Since the pandemic, the digitalization of practical educational activities has been a central focus of pedagogical practices, leading to the development of specific engineering workflows. These integrate software and hardware solutions aimed at the implementation of XR experiences that fulfil the intended learning outcomes of the engineering product, process, and system design. In this paper, we present the design of an educational workflow for integrating manufacturing systems in XR-based learning environments. Two use cases are presented to demonstrate the relevance of the proposed workflow. The first provides an interactive experience that transfers laboratory teaching practices for pneumatics systems into an augmented reality (AR) application. The second focuses on the visualization and learning of direct kinematics methods for an industrial robotic arm.

1. Introduction

Extended reality (XR) in the role of advanced interface for cyber-physical systems, data visualization, and aid for human-robot collaboration platforms has been one of the pillars of the fourth industrial revolution [1] and the core of the new Industry 5.0 paradigm [2]. As XR applications have become increasingly popular and found their way into supporting different tasks in industry [3], and, of course, other domains, they have also been adopted in higher education both as an educational support tool [4], especially with hands-on and technical work (e.g., virtual laboratories), and as advanced systems prototyping technologies. The importance and impact of these systems is expected to be even more dominant in the coming years [5]. Consequently, there is a need to guide new generations of students to adopt XR natively in the design, prototyping, and training processes.

This work presents the XR tools to support learning activities in engineering education with the dual goal of enhancing hands-on training on these specific technologies, while improving existing courses and providing a test bench for students to integrate advanced digital tools natively in product, production process, and manufacturing systems design. The publication focuses on the development of a workflow for manufacturing process and system design and presents two use cases, resulting in applications developed and tested by the students at Tallinn University of Technology.

2. Related works

The adoption of advanced digital tools and distance learning, caused by the pandemic, has been growing in the last years due to the technological development in the XR domain and the increasing need for digitally available teaching resources. The benefits of XR applications in engineering education are clear and supported by a variety of studies and applications. Increased grade performance, understanding of the subjects, engagement but also increased lab accessibility, cost reduction for equipment and lab spaces, and teaching time reduction, especially related to repeatable tasks, are some of these advantages [6]. This also comes with some drawbacks, including the need for continuous evaluation and improvement of the proposed systems, a lack of skills in the XR domain, as well as the integration of learning theories and design tools into engineering curricula [7], which is partially the goal of the presented activities. Moreover, the role of a human worker in the modern digital industrial era tends to be supportive, related to overseeing, managing, and collaborating with automated systems. Thus, workers need a new set of competencies that include digital, technical, interdisciplinary, and collaborative skills. For that reason, educational institutions must adapt new teaching methods and materials to prepare students for these evolving technologies in engineering [8]. XR and immersive simulations that transform work and education require both industry and institutions to embrace new approaches and skills to stay relevant. The concept of learning factories, integrating virtual and augmented realities, provides manufacturing systems and processes for learners on a model scale, facilitating lower investment, increased obtainability, and higher safety levels [9]. In the same way, the development and testing of virtual learning factory toolkits help to enhance digital skills by exploiting enabling technologies of simulation and virtual reality (VR) in manufacturing studies and education projects with industrial use cases [10]. The focus of this work is to establish a holistic workflow by integrating XR for learning activities supported by digital tools.

3. Proposed workflow

The definition of an appropriate workflow for the given tasks is based on previous academic teaching experiences and rooted in the general framework of virtual learning in the engineering education presented in [11]. The proposed workflow consists of several phases, starting from understanding the selected system, defining the requirements, and progressing through to testing and evaluating the proposed XR system integration and the learning activities associated with it. These phases run parallel to specific tasks and actions that students are expected to complete at each stage, serving as general guidelines adaptable to individual use cases. Additionally, an overarching element involves selecting digital tools to support the implementation of XR technologies into each step of the process. The workflow is shown in Fig. 1.

The *Understand* phase relates to the conceptual knowledge behind the selected process, the understanding of theories, models and structures, and the correct use of terminology and object properties. Furthermore, these initial steps focus on the analysis of the manufacturing system and process, which in most cases comprises the integration of different resources, procedures, and a multidisciplinary development approach. The types of resources, how these are integrated, and the technologies selected for the development will largely influence the performance of the system and the adoption of specific key performance parameters (KPIs) or assessment metrics in the *Validate* phase. Other than KPIs, this last step concentrates on the validation of the digital environment (real-time rendering and animations performance) and user-related metrics for usability, user experience (UX), as well as effectiveness and efficiency of the system. During the *Create* phase, students provide a selection and classification of the system's components and resources, such as inputs, outputs or human resources, technical equipment, and manufacturing parts. Specific modeling and mapping tools can be used in this phase (e.g., Microsoft Visio, Miro, Mural) to define the process flow, machine/human-related tasks, and data or software architecture. The definition of tasks, process flows and procedure analysis goes in parallel with the creation and selection of the appropriate assets (e.g., 3D models, software components, software development kits (SDKs)) to be integrated into the XR environment. These assets are retrieved through the producers' company repositories or are custom-made. Before prototyping the XR scenarios, other simulation tools can be leveraged for preliminary integration and performance evaluation (e.g., Visual Components, Siemens Plant Simulation, AnyLogic). The *Prototype* phase is directly related to the selection (*Select* phase) of the XR hardware and software

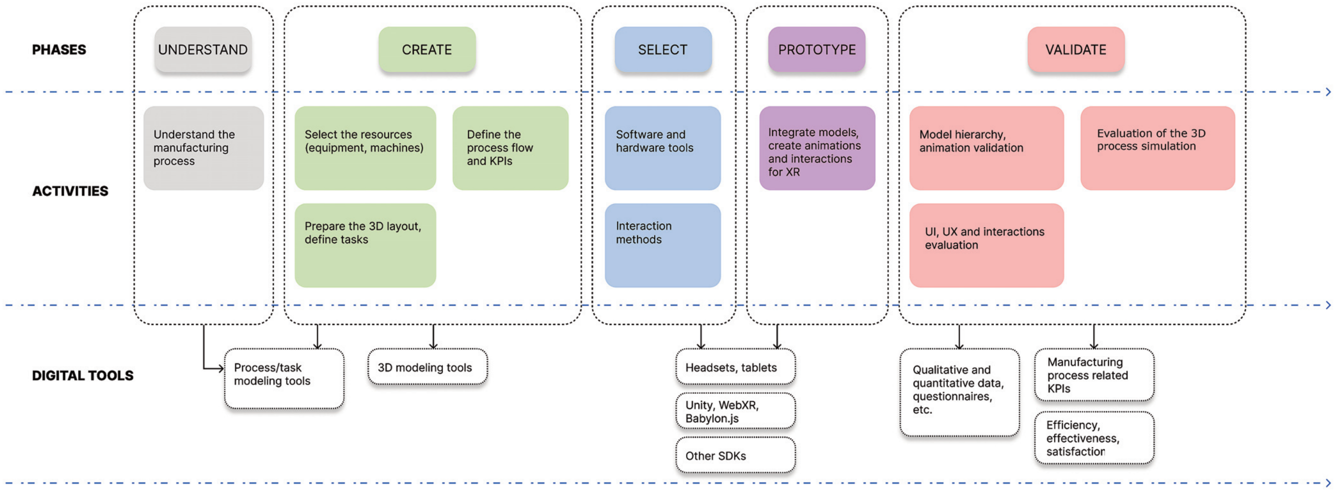

Fig. 1. Workflow for integration of XR technologies in a manufacturing process.

solutions. These include the visualization and interaction equipment and are based on the planned scope and requirements of the software. Regarding the hardware, the options could range from augmented reality (AR) headsets, fully immersive VR headsets, and hand gesture tracking to the use of physical controllers, data gloves, desktop-based setups, tablets, or other hand-held devices. Depending on the application's portability requirements, the software architecture might adopt a standalone solution (e.g., by using Unity, Unreal Engine) and dedicated SDKs or web-based software frameworks and libraries.

4. Use cases

Two applications have been developed at Tallinn University of Technology by two groups of students during the study semester courses in parallel to the above-mentioned project activities and in collaboration with their peers in various higher education institutions. The first use case aims at the development of XR tools in the hydraulics and pneumatics laboratory course. The second focuses on the integration of advanced kinematics and visualization tools for robotics training, specifically for robotic arms, at the TalTech Flexible Manufacturing and Robotics Demo Center.

4.1. Pneumatics system assembly

The pneumatics laboratory offers a hands-on learning experience conducted in groups of three. The lab is divided into two sessions: pneumatics and electro-pneumatics. Each session runs for three hours. Students typically take from three to five sessions to complete the program. As for each hands-on course, students are initially instructed about safety measures and the basics of the theory behind the practical experience. This usually requires them to assemble a circuit by using the components provided and by following a schematic drawing. The workbenches and components used during the course are visible in Fig. 2.

The resulting assembly is checked by the tutor and verified with the student in its functioning. One of the goals of the XR application is to facilitate the repetition of the tasks without needing the access to laboratory equipment, which is limited and needs constant supervision. This would allow students to train on the assembly tasks ahead of the laboratory experience and in a safe environment, facilitating the exploration of the theoretical concepts and becoming familiar with the components and their functioning. Students divided the necessary activities for development based on the provided workflow with necessary adaptations. After an initial analysis and definition of the above-mentioned application goals, digital assets were created for each component and necessary furniture element of the lab. The software architecture was defined by considering the frontend, representation and interaction layer, and backend with the components' twin representation, connection state, air flow simulation, piping, and algorithms dedicated to simulation and exercise verification (Fig. 3).

Fig. 2. The pneumatics and hydraulics laboratory. Photos taken by the authors.

Ensuring the application's accessibility and availability is critical for this use case. End users must be able to engage with the proposed exercises from any location and across various hardware platforms. To meet these requirements, a web-based application was developed using JavaScript libraries such as NEXT.js [12], Three.js [13], and WebXR APIs [14] to incorporate XR functionalities. This approach allows for access through any web browser that supports XR on a wide range of devices, including desktops, headsets, and hand-held devices. For the specific prototype, the Meta Quest 3 was chosen as the primary device for interaction and visualization. Students opted for a hardware-free interaction solution by utilizing the Meta Quest's hand-tracking capabilities. An example of the XR application developed for this

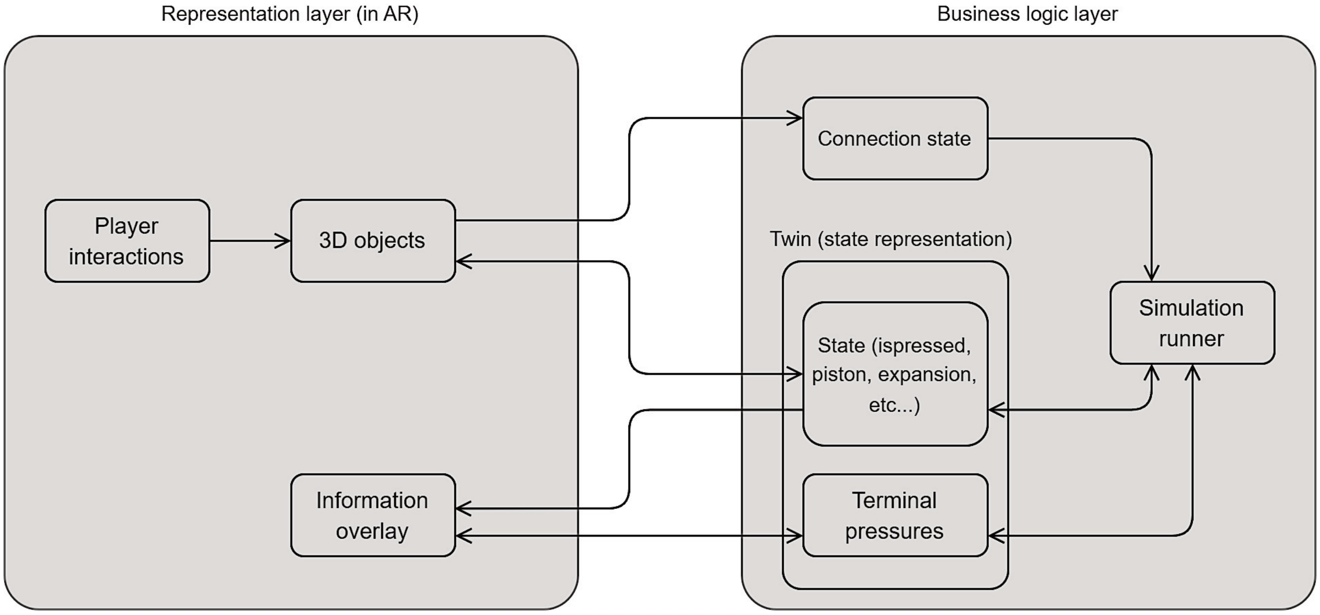

Fig. 3. Software architecture and application logic.

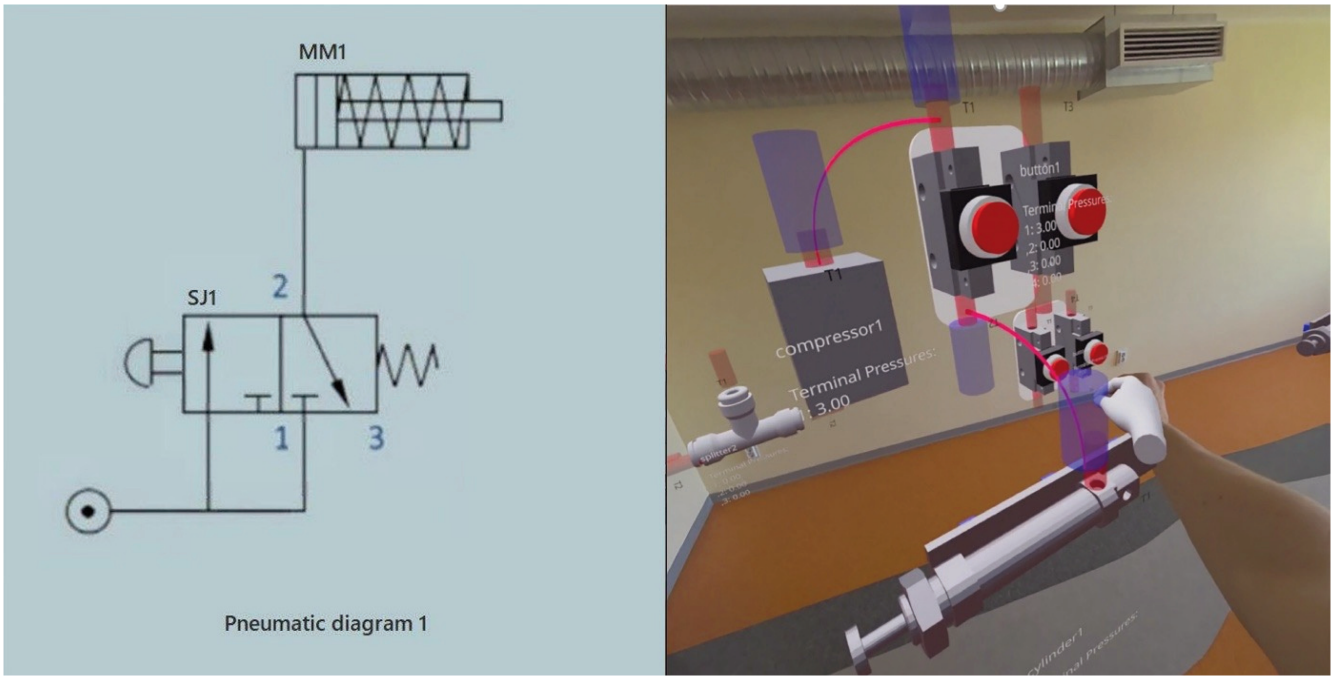

Fig. 4. AR application prototype with a single acting cylinder.

use case is exemplified in Fig. 4. The image shows one of the proposed exercise schematics and a user interacting with the virtual objects to compose the circuit.

An experimental comparison was conducted between two exercises, evaluating performance and user experience during task completion in the physical laboratory and its virtual counterpart. Some of the metrics defined in the initial design phase were adopted during the assessment, including exercise completion rate, time to complete the task, number of attempts, and subjective evaluation of user satisfaction.

4.2. XR-based direct and inverse kinematics simulations

The second use case focuses on the integration of inverse and forward kinematics teaching (IK, FK) for two robotic arms, Yaskawa Motoman GP8 [15] and ABB IRB 1600 [16] (Fig. 5), which are used in different courses attended by mechanical and industrial engineering bachelor and master students at Tallinn University of Technology.

The main goal is to provide a sandbox for testing kinematics algorithm solvers and advanced robotics system control in a safe and repeatable way. The application is developed as an immersive VR environment, allowing visualization of the two robots, interaction and motion planning, as well as an interactive visualization of the homogeneous matrix transformations and the Denavit–Hartenberg convention for the FK. Connected to the latter, a few FK exercises proposed in the application are taken from [17]. The digital twins (DTs) of the two robotic arms are integrated into the simulated environment using the Unified Robot Description Format (URDF) [18]. An initial task and user experience

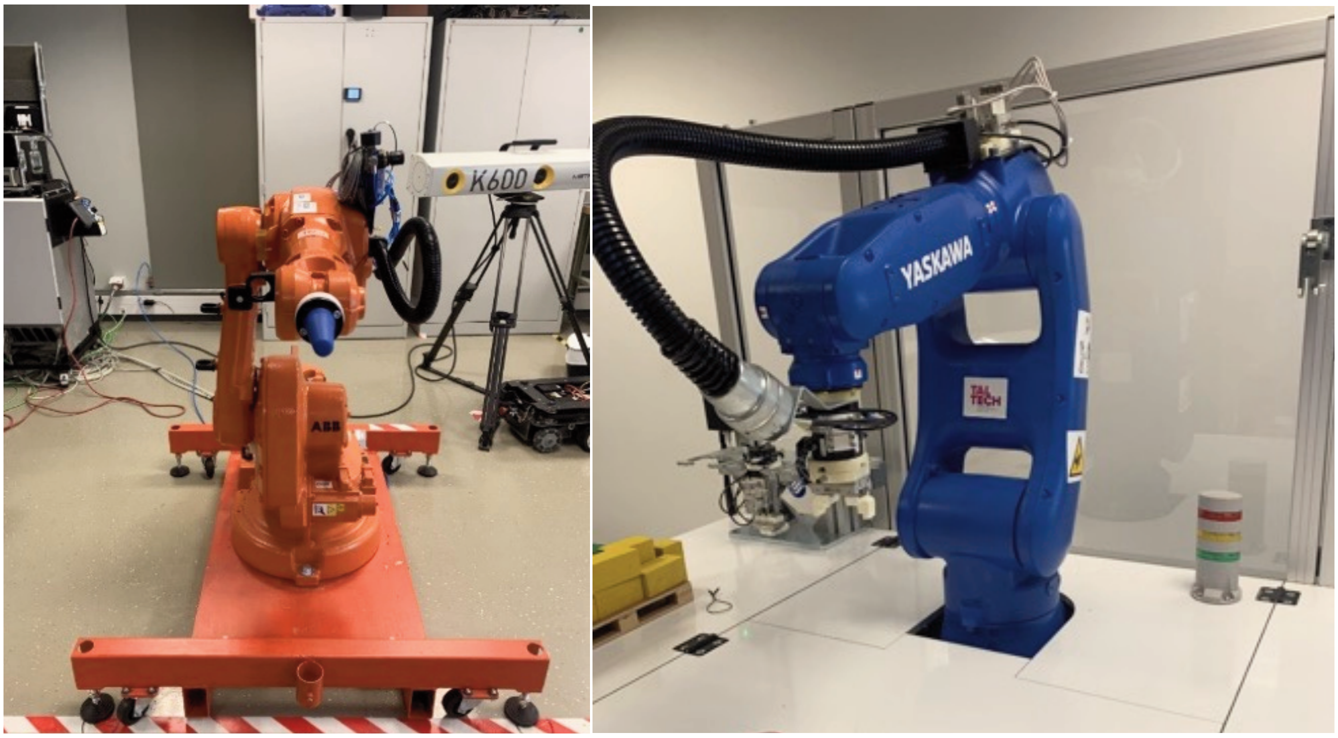

Fig. 5. ABB IRB 1600 and Yaskawa Motoman GP8 robotic arms. Photos taken by the authors.

Fig. 6. ABB IRB 1600 and Yaskawa Motoman GP8 digital twins and interactive kinematics application prototype.

analysis define the type of user interaction and interface elements required in the application. Custom scripts provide the kinematics solver and FK visualization integration. Meta Quest 2 headset is selected for VR visualization, offering inside-out tracking, hand gesture tracking, and see-through capabilities. Unity [19] is chosen as the development platform, leveraging C# for custom scripts and integrating the Meta Quest SDK and Unity UI package. Unity to ROS custom scripts proposed in [20] are leveraged to connect to the real robot counterparts and control them from the simulated environment. Hand tracking is adopted as the primary interaction method, enabling intuitive control of virtual assets without additional hardware. Two gestures were defined: Poke Interaction for UI interaction and Grab Interaction for the path planning tool in the IK solution for the ABB robot. A prototype of the application is shown in Fig. 6.

5. Conclusion

The integration of XR technologies in engineering education is crucial for adapting to Industry 5.0. Students must gain experience with XR-based prototyping and development tools, using them for both learning and advanced design in cyber-physical systems. These skills prepare them for industry demands, ensuring competitiveness in the digital era. This study addresses these needs by proposing a framework and workflow to enhance learning and modernize laboratory teaching with cutting-edge technology. Two use case applications based on the above-mentioned workflow have been successfully developed and presented in this study. Future works will consider full integration of the tools in the course curricula and a comparative evaluation of the benefits and improvements on the learning outcomes of each course. User studies are already taking place, comparing the effectiveness and user experience for the pneumatics XR teaching application with the traditional documentation. Results of these experiments will be considered for future publication. Additional use cases will be developed to improve laboratory teaching practices with XR interaction and visualization tools.

Data availability statement

All research data are contained within the article and can be shared upon request from the authors.

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References

1. Kagermann, H., Wahlster, W. and Helbig, J. *Recommendations for implementing the strategic initiative Industrie 4.0. Final report of the Industrie 4.0 working group*. Forschungsunion, Berlin, Germany, 2013.
2. Pizzagalli, S. L. *Extended reality for I5.0: towards human centricity in human-robot interaction*. PhD thesis. Tallinn University of Technology, Estonia, 2024.
3. Damiani, L., Demartini, M., Guizzi, G., Revetria, R. and Tonelli, F. Augmented and virtual reality applications in industrial systems: a qualitative review towards the Industry 4.0 era. *IFAC-PapersOnLine*, 2018, **51**(11), 624–630. https://doi.org/10.1016/j.ifacol.2018.08.388
4. Terkaj, W., Kleine, K. and Kuts, V. Virtual labs for higher education in industrial engineering. *Proc. Estonian Acad. Sci.*, 2024, **73**(2), 142–149. https://doi.org/10.3176/proc.2024.2.07
5. ECORYS. *XR and its potential for Europe.* Brussels, 2021. https://xreuropepotential.com/assets/pdf/ecorys-xr-2021-report.pdf (accessed 2025-01-13).
6. Soliman, M., Pesyridis, A., Dalaymani-Zad, D., Gronfula, M. and Kourmpetis, M. The application of virtual reality in engineering education. *Appl. Sci.*, 2021, **11**(6), 2879. https://doi.org/10.3390/app11062879
7. Takrouri, K., Causton, E. and Simpson, B. AR technologies in engineering education: applications, potential, and limitations. *Digital*, 2022, **2**(2), 171–190. https://doi.org/10.3390/digital2020011
8. Christiansen, L., Hvidsten, T. E., Kristensen, J. H., Gebhardt, J., Mahmood, K., Otto, T. et al. A framework for developing educational Industry 4.0 activities and study materials. *Educ. Sci.*, 2022, **12**(10), 659. https://doi.org/10.3390/educsci12100659
9. Büth, L., Juraschek, M., Sangwan, K. S., Herrmann, C. and Thiede, S. Integrating virtual and physical production processes in learning factories. *Procedia Manuf.*, 2020, **45**, 121–127. https://doi.org/10.1016/j.promfg.2020.04.082
10. Mahmood, K., Otto, T., Kuts, V., Terkaj, W., Modoni, G., Urgo, M. et al. Advancement in production engineering education through Virtual Learning Factory Toolkit concept. *Proc. Estonian Acad. Sci.*, 2021, **70**(4), 374–382. https://doi.org/10.3176/proc.2021.4.02
11. Terkaj, W., Urgo, M., Kovács, P., Tóth, E. and Mondellini, M. A framework for virtual learning in industrial engineering education: development of a reconfigurable virtual learning factory application. *Virtual Real.*, 2024, **28**(3), 148. https://doi.org/10.1007/s10055-024-01042-8
12. Next.js. https://nextjs.org (accessed 2025-01-11).
13. Three.js. https://threejs.org (accessed 2025-01-11).
14. WebXR. https://immersiveweb.dev (accessed 2025-01-11).
15. Yaskawa. https://www.motoman.com/en-us/products/robots/industrial/assembly-handling/gp-series/gp8 (accessed 2025-01-13).
16. ABB. https://new.abb.com/products/it/3HAC021770-001/irb-1600 (accessed 2025-01-13).
17. Spong, M. W., Hutchinson, S. and Vidyasagar, M. *Robot Modeling and Control*. 2nd ed. John Wiley & Sons, 2020.
18. ROS. https://wiki.ros.org/urdf (accessed 2025-01-13).
19. Unity. https://unity.com/ (accessed 2025-01-13).
20. Kuts, V., Otto, T., Tähemaa, T. and Bondarenko, Y. Digital twin based synchronised control and simulation of the industrial robotic cell using virtual reality. *J. Mach. Eng.*, 2019, **19**(1), 128–145.

Laiendatud reaalsusel põhinev töövoog insenerihariduses õppimiseks

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Tööstuse 4.0 arengust kasutajakesksema tööstuse 5.0 paradigmani liikudes mängivad täiustatud laiendatud reaalsuse (XR) tehnoloogiad olulist rolli tootmise ja tööstuse kontekstis, muutes seda, kuidas lõppkasutajad pääsevad juurde küberfüüsikalistele süsteemidele ja reaalajas andmeallikatele ning neid kontrollivad. See kehtib nii reaalse tootmiskeskkonna kui ka kõrgkoolide kohta, kus tulevased insenerid õpivad neid tootmissüsteeme projekteerima ja juhtima. XR on muutunud tööstuslike inimese-masina interaktsioonimeetodite lahutamatuks osaks, sealhulgas diagnostiliste andmete visualiseerimisel, teleoperatsioonil, täiendatud hoolduse ja kokkupaneku juhiste rakendamisel ning raskete masinate ohutul käitamisel. Hariduskontekstis võimaldab XR praktilisi virtuaalseid tegevusi, ressursside suuremat kättesaadavust ja korduvvõimalusi enne laboripraktikume. Pandeemia järel on praktiliste õpitegevuste digitaliseerimine saanud pedagoogiliste praktikate keskseks fookuseks, viies konkreetsete inseneritöövoogude arendamiseni. Need töövood integreerivad tark- ja riistvaralahendusi, et rakendada XR-kogemusi, mis toetavad inseneritoodete, -protsesside ja -süsteemide disaini õpiväljundeid. Artiklis tutvustame hariduslikku töövoogu tootmissüsteemide integreerimiseks XR-põhistesse õpikeskkondadesse. Esitame kaks kasutusjuhtumit, mis demonstreerivad pakutava töövoo asjakohasust. Esimene pakub interaktiivset kogemust, mis viib pneumaatiliste süsteemide laboriõppepraktikad liitreaalsuse rakendusse. Teine keskendub tööstusliku robotkäe otsekinemaatika meetodite visualiseerimisele ja õppimisele.