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Educational teleoperation platform for heavy industrial robotics as a learning environment

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Abstract

The ongoing digital transition affects the manufacturing industry at many levels. Emerging technologies such as robotics, human-robot collaboration (HRC), artificial intelligence (AI), and cyber-physical production systems (CPPS) are enablers of Industry 4.0. The objective of the forthcoming Industry 5.0 is to establish the creativity of human experts in collaboration with intelligent machines and production systems to achieve resource-efficient and user-preferred manufacturing solutions. However, only a limited amount of physical learning environments is available for learning the skills required by Industry 5.0. In their previous work, Kaarlela et al. [1] introduced a novel robotics teleoperation platform enabling remote access to industrial robotics laboratories to train students online with physical equipment. The presented teleoperation platform allows the usage and learning of robotics remotely independently of time and location. The platform enables teleoperation, remote control, and near real-time monitoring of controlled robots. The functionality of the teleoperation platform in the education of lightweight industrial and collaborative robots is proven. However, there is a need to test the proposed technology in heavy industrial robotics and analyze on a more detailed level what kind of learning environment it is. This paper will prove the applicability of the proposed platform in the education of heavy industrial robotics by analyzing the suitability of the teleoperation platform as a learning environment. Analyzing is carried out according to the defined criteria of an effective learning environment. The paper also presents a developed learning path for utilizing the teleoperation platform in the teaching of industrial robotics.

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1. Introduction

Industry 4.0 focused on the emerging technologies such as human-robot collaboration, artificial intelligence, internet of things, and cyber-physical production systems [2]. The forthcoming Industry 5.0 concept emphasizes the human aspect, along with the resiliency and environmental sustainability [3]. One of the objectives of Industry 5.0 is to achieve resource-efficient yet user centric manufacturing solutions [4]. New technologies emerge faster than the workforce's capability to adopt them [5]. New technologies require new educational practices to eliminate skill gaps and improve existing skills [6]. Abele et al. [7] noticed that modern concepts for training, industrial learning, and knowledge transfer are required to keep up with development. Manufacturing as a subject cannot be taught efficiently only in a classroom; there is a need for practical laboratory exercises [8].

However, sometimes the laboratory resources are limited [8]. For this reason, there have been research around mobile educational learning cells [6] and industrial online learning [9] and training environments [10] in recent years. There are multiple different digital twin (DT) and virtual reality (VR) applications, e.g. [11, 12], to teach and train larger masses. However, moveable educational cells and online learning environments might not be

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enough for teaching of more heterogenous and distributed audience. There have been research around industrial remote learning environments, which integrates online learning platform directly to physical equipment [13, 14] and increases laboratory utilization rate. For industrial robotics education, there is a need for an educational robotic teleoperation platform where a human operator controls a physical robot over a data connection. For this, Kaarlela et al. [1] have introduced a novel educational teleoperation platform for industrial robotics training. There bi-directional communication enables a student to control a robot at the university laboratory from any location through an online connection. In this method, the user can utilize an online user interface to monitor the status of the robot and remotely control the robot with near real-time live footage from the laboratory [1].

This paper continues the work initiated by Kaarlela et al. [1]. The aim of the teleoperation platform is to train future robot specialist remotely. Within this platform students can understand the basics of the robotics, such as movements of the robot. The first target is to scale this technology from lightweight industrial and collaborative robots to heavy industrial robots. The second target is to evaluate the suitability of the teleoperation platform as a learning environment according to the defined criteria of an effective learning environment. The third target is to introduce the developed learning path for using the teleoperation platform in higher education.

The rest of the paper includes the following topics. Section 2 presents the technical implementation for the remote operation where technology scales to heavy industrial robots. Section 3 defines the criteria for an effective learning environment and Section 4 evaluates the teleoperation platform against the criteria. Section 5 presents the developed learning path for using the teleoperation platform in higher education and Section 6 concludes the paper and defines the next steps for the future research.

2. Technical implementation for the remote operation

Technical implementation of the teleoperation platform for heavy industrial robots has been verified in two different learning environments. Proving the integrability and scalability of the proposed technology in heavy industrial robotics. The first learning environment is the Robo3D Lab at Centria Ylivieska, and the second is the Human-Robot Collaboration Pilot Line (HRC Pilot Line) [15] at the Tampere University presented in Fig 1. In their previous implementation, Kaarlela et al. [1] used Fanuc LR-Mate industrial robot, intended for educational purposes, and Universal Robot UR3 collaborative robot, an inherently safe robot type. Both robots have six rotary joints for positioning and a two-finger gripper for attaching and detaching work pieces. Payloads and reaches of the robots are relatively small, which is why the proposed technology requires testing with heavy industrial robots with different system dynamics. For this purpose, technology is scaled to ABB IRB4600 (HRC Pilot Line) and ABB IRB6700 (Robo3D Lab) robots mounted on linear tracks. Both robots feature high payloads, large reaches, six rotary joints, linear tracks, and grippers for attaching and detaching work pieces.

Fig. 1. HRC Pilot Line.

Safety is one of the key concerns when implementing teleoperation for heavy industrial robots, which are not inherently safe. Based on the risk assessment, the main risk is that someone in the lab ends up in the robot's operating space during remote operation. In addition to physical safety fences, safety-approved electrical devices such as light curtains, door switches, and safety scanners secure the robot working areas. Electrical safety devices identify users violating the robot's work area and stop the robot's movement. Light beacons indicate the system

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status to the people in the laboratory. Alongside physical and electrical safety devices, the SafeMove option [26] monitors robot motion and safety devices to avoid collisions and movements of the robot to forbidden areas. SafeMove also performs robot tool supervision and limits the speed of the robot. With this setup, robot movements isolate to predefined permitted areas, the movement speeds of the robot are in control, and tool supervision prevents collisions between the tool and the surrounding static environment. In addition, near real-time webcams enable the monitoring of laboratories. Webcams provide a wide view of the laboratory allowing the remote user to detect and to notice forbidden personnel in laboratory.

The detailed system architecture is presented in the previous work [1] but the main principle is shown in Fig 2. For this implementation, the main development steps were to connect ABB robots to the current system architecture and to develop user interfaces for the teleoperation of the robots. ABB robots have the option to support data transmission with Message Queue Telemetry Transport (MQTT) protocol. Support for the MQTT protocol requires the installation of the IoT Data Gateway software [27]. IoT Data Gateway enables the transfer of data, such as robot joint positions, from the robot to the user interface. However, IoT Data Gateway does not support data transmission from the user interface to the physical robot, which means the user cannot control the robot via the user interface with this protocol. Enabling bi-directional data transmission between the user interface and the physical robot required a custom MQTT/OPC UA (Open Platform Communications United Architecture) bridge written in Python.

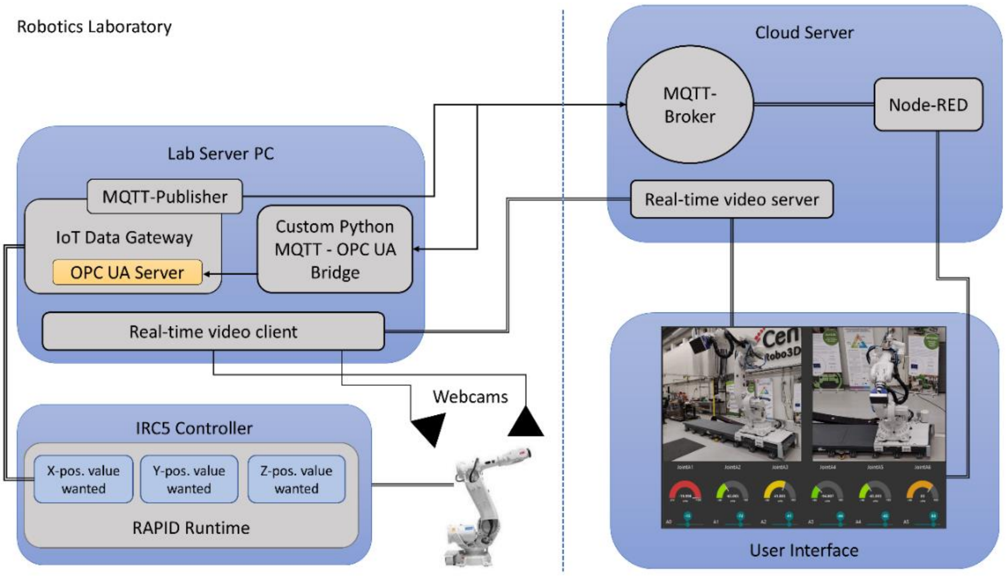

Fig. 2. Implementation of the teleoperation platform at the Robo3D Lab.

The user interface for the ABB IRB6700 robot, presented in Fig. 2, is implemented with the Node-RED development tool. The user interface provides near real-time live footage from the robot cell, presents individual joint values of the robot, utilizing gauge elements, provides buttons to control the gripper (open/close) and sliders to control robot movements in linear X, Y, and Z directions. The user interface transmits desired X, Y, and Z position values and desired gripper status via a custom MQTT/OPC UA bridge to the robot's RAPID program, ABB's native programming language for the robot. The actual program for the robot control is in RAPID.

3. Criteria of the teleoperation platform as an effective learning environment

The presented teleoperation platform has already been used in the teaching of bachelor students in simple lightweight robotic pick and place tasks. Initial free-form feedback from the students and teachers has been positive [1]. Although the feedback has been promising, the technology's suitability for teaching still needs to be proven. To demonstrate suitability, the teleoperation platform is analyzed based on the developed criteria of an effective learning environment, presented in the Table 1. The criteria have been derived from [1, 6, 13, 15-18] and further developed by the robotics experts teaching at the Centria and Tampere University. Some of the criteria are more related to the pedagogical usability (does the learning platform enable student to reach the learning goals [17]) of the teleoperation platform and some to the technical usability, e.g. Nielsen's heuristics for user interfaces [19], of the teleoperation platform in education. Next, suitability of the teleoperation platform for educational use is carried out as a qualitative analysis according to the presented criteria.

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Table 1. Criteria for an effective learning environment.

Criteria	Description/Target
Authentic learning	Authentic learning is an educational approach that supports students to explore, discuss, and construct concepts and relationships in contexts involving real working life problems [20].
Collaborative learning	Collaborative learning is based on social interaction between members of a group. Group members actively interact to construct new knowledge and learn new skills by utilizing other's resources and skills [21]. Social interaction is crucial for effective online learning [22].
Competence-based learning	Competence-based learning is a learning outcome-based, student-centered learning framework where students progress to more advanced work once mastering the prerequisite skills and content [23]. Learning environment should provide personal study paths [18].
Connections to other learning environments	Through the network limited teaching resources can be shared and present widespread knowledge and skills in one place accessible to everyone on the network [8].
Ease of use (including learnability and memorability)	System should be easy to use meaning that novice user should learn quickly to use the system for productive work and occasional user to recall essential features of the system [17].
Enables different pedagogical practices	Versatile teaching, guidance, learning, feedback, and assessment methods can be utilized in the learning environment. Learning environment follows the guidelines of constructive alignment, mixes different learning theories, and provides an opportunity to digital pedagogics. [18]
Open access (including accessibility and availability)	Available, accessible, and inclusive learning environments. Learning environments are available for everyone with flexible hours and enables chance to study at the learning environment regardless of personal characteristics or different life situations [18].
Promotion of student agency	Student agency is the ability to set a goal, reflect, and act responsibly to make the decisions and choices instead of accepting the decisions and choices made by others [24].
Safety and security	Safe use of the laboratory equipment without harming user, personnel, and equipment. Cybersecurity is a crucial safety issue for an online (learning) platform [25].
Technical usability (both user interface and system)	The user interface of an online application must be easy and effective to use so that the operator can concentrate on the information content [14] and learning [17] instead of the interface. System should be technically reliable and recoverable to initial state [19].

4. Evaluation of the teleoperation platform as a learning environment

The teleoperation platform is an authentic learning environment in that sense that it provides a remote online 24/7 open access to real heavy industrial robot cells. Users can control real robots to implement real-life assembly scenarios and analyze real-life system dynamics which isn't possible when programming robots in an offline programming software. Controlling of the robots is made easy with the simplified and reconfigurable user interface. Remote controlling is carried out utilizing the sliders and buttons; thus, the user doesn't need to focus on to the programming language of the robot. A common user interface is handy as the same user interface can be used to remote control different robot brands utilizing different programming languages and user interfaces.

The teleoperation platform enables safe introduction to heavy industrial robotics remotely without endangering the user. Introduced platform provides a live chat, a discussion forum, and real-time online video meeting options for collaborative learning and a booking calendar where students can select an optimal time for their exercises. Through these communication channels, students can exchange ideas and solve problems together and if needed get guidance and support from course personnel. Remote operation of the robot provides students an opportunity to discover new dimensions of robotics and modern technology actively on their own without constant supervision, thus promoting student agency. The teleoperation platforms for the ABB robots presented in this paper are part of the network of teleoperation platforms. The network consists of learning environments for different robotics and automation applications from Finland, Norway, and USA, all available for students.

Although the teleoperation platform has features of an effective learning environment, there are still some deficiencies. The user interface of the teleoperation platform doesn't correspond to the robots' natural user interface. Thus, students don't learn to program robots utilizing native programming languages and environments. Current student exercises are mostly implemented with simplified pick and place activities with simple objects such as boxes, not with the authentic complex industrial products. At the moment, the teleoperation platform is mainly intended for introduction courses where the beginners have a limited amount of experience in industrial robotics. Although, the difficulty level of the exercises rises during the courses these are still very simple exercises. Thus, the teleoperation platform doesn't support competence-based learning on a higher level. Current version of the teleoperation platform has major problems with error recovery when either user makes a mistake, e.g. drops parts to a floor, or when robot faces a system failure, e.g. singularity error. User interface doesn't indicate if there is a system failure on the robot. The robot has to be manually recovered at the laboratory before work can continue.

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5. Development of the learning path of the teleoperation platform

As discussed in the previous section, current student exercises at the teleoperation platform are mainly intended for beginners and are separate simple pick and place applications. There is a need to develop a learning path for utilizing teleoperation platform in education to support both constructive alignment and competence-based learning with different pedagogical practices. The developed learning path is presented in Fig 3.

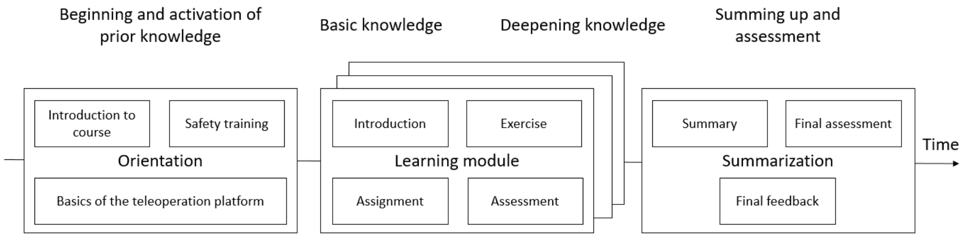

Fig. 3. Basic structure and timeline of a learning path.

Learning path starts with the orientation to the course topic and to the teleoperation platform. Students get familiar with the course policy and learn how to use the teleoperation platform in a lecture. Before the lecture, students familiarize themselves with the operating principles of the teleoperation platform with offline learning materials (documents and videos) provided via web-platform. After the lecture, students will take an online safety training exam for the teleoperation platform. The exam shows that the students understand the basic safety and operating principles of the teleoperation platform before starting to work independently on the platform.

Learning path consists of different learning modules with a predefined structure. Modules are structured with different topics, starting from the beginner level topics and moving towards expert level topics. The target is that the students start working with the teleoperation platform to learn the basics of robotics and after mastering this they will move on to work with the physical robots with their native programming languages and environments. There are topics related directly to the use of the robot, e.g. creating simple pick and place applications with simple objects or advanced pick and place applications with industrial products. There are also other topics related to the robotics, such as robotics safety, safety devices at the robot cells, and gripper and feeder design for robot applications. Every learning module starts with the introduction to the intended learning outcomes, teaching and learning activities and assessment guidelines alongside core content of the module which provides the basic knowledge of the topic for the students. This can be done with pre-recorded videos, literature or in an online meeting: teacher gives a lecture at the laboratory and students follow teaching through the teleoperation platform. After the introduction, every module includes an exercise or a demonstration which introduces students to the actual collaborative assignment to be completed independently by the students. Assignments deepen students' knowledge as the assignments utilize problem-based learning with real working life problems. After completing the assignment, students return a video clip of the working system, and/or a report. Students will receive feedback on their performance, and plausible example solutions provided by the teacher, before moving on to next module.

At the end of the course, the whole course content is summarized. The students should return final reports of their findings based on to the core and advanced contents of the individual learning modules. For good learning results, students should perform self-reflection about what they have learned. Individual assignments are assessed during the course, but the final assessment is done and assessed at the end of the course.

6. Conclusion

The paper aimed to prove the applicability of the teleoperation platform in heavy industrial robotics and evaluate the suitability of the teleoperation platform as a learning environment according to the defined criteria of an effective learning environment. Final target was to develop learning path for utilizing the teleoperation platform in the teaching of industrial robotics. As a result, teleoperation platforms for heavy industrial robots were implemented successfully in two different laboratories. The biggest challenges were the data transfer between the robot and the user interface and guaranteeing the safety of the laboratory staff during the remote control of the robot. The criteria for an effective learning environment suitable for the teleoperation platform was presented. Based on the criteria, the suitability of the teleoperation platform as a learning environment was evaluated. As a result, the teleoperation platform is currently suitable for training beginners in simple robot applications and there is a need to develop authentic and competence-based learning paths towards expert level training. Hereby, the learning path for using the teleoperator platform in teaching is presented.

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The teleoperation platform is still on the development level. There are some limitations on both technical and pedagogical side that require future research. First development task is to add the capability to record program lines to create programs for the robot. Then teleoperation platform isn't just for the remote control of the robot but also used learning robot programming and creating the robot programs. An intelligent tutoring and recovery system is needed for the teleoperation platform to guide students to recover from typical error situations. From the pedagogical point of view, appropriate learning indicators should be identified and documented to analyze how effective learning really is on the teleoperation platform. Also, the impact and importance of the developed teleoperation platform for educational use should be analyzed in a quantitative manner.

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