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Applicability of Augmented and Virtual Reality for Education in Robotics

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Abstract:
The rapid development of automatic control and robotics requires an innovative approach to teaching. This is especially important in the case of studies at the academic level and in vocational schools, where training with expensive robotic stations is necessary. A solution to this problem may be substituting these with augmented reality (AR) and virtual reality (VR) due to their significantly lower costs. AR/VR technologies have an advantage in terms of low-cost and effective practices in robotics. The described content is an outcome of the MILAN project, wherein those technologies are used for the purpose of online courses. This includes providing access to virtual laboratories via a mobile application and the real-life training stations connected to the network. This paper provides an overview of the available AR/VR applications implemented in robotics education and a detailed description of related best practices. The main sections contain a detailed methodology for designing an AR mobile tool for learning robotics in the AR environment. Moreover, the main challenges encountered during the development phase were listed and analysed. Additionally, this paper presents the possible future use of the application with the associated benefits. The literature overview and conclusions may be used to design similar online courses with an interactive form of teaching practical industrial robots programming.

Keywords: *Augmented Reality, Education, Industry 4.0, Robotics, Virtual Reality*

1. Introduction

The rapid development of automatic control and robotics, as well as the spread of the Industry 4.0 paradigms , made current teaching methodologies ineffective [1]. Meanwhile, the current labour market situation forces the creation of new approaches to teaching. The effective methods should be widely available. Moreover, they should be possible to be used even without specialised equipment. Creating them according to the proposed methodology would support online learning and, thus, stop the deterioration of the education quality caused by the COVID-19 pandemic [2]. AR applications in particular may help to keep education at the highest level. The described methodology is based on substituting real-life industrial setups with their interactive models in AR/VR. This will lead to raising the quality of teaching at universities in small towns, which do not have sufficient resources to provide a proper learning setup, e.g., a setup with enough robots and industrial devices required for effective practice. The most promising trend related to this is implementing augmented reality technology using smartphones with the Android system as the most available and easiest scalable.

2. Overview of the existing solutions

AR / VR technologies are widely applied for educational purposes due to their innovative capabilities. However, most developed applications demand highly specialised equipment such as VR / AR goggles or additional controllers. This section contains an overview of already used solutions. As to create an up-to-date application, the selected best practices were analysed. The Scopus and Google Scholar databases were involved in searching for available papers. When using the Scopus database, the following keywords were imputed: AR, VR, Robotic, Education. During the search, the publication time of papers was limited to 2018 and above, while the field of science was limited to engineering. Such a search resulted in ten papers, of which only three were selected as considerably related to the topic of research and had a detailed description of created applications. The Google Scholar database was searched based on the following queries: AR in robotic education, VR in robotic education, AR in education, VR in education, AR VR industrial robotic training. In this case, the publication time of the paper was also limited to 2018 and above. After selecting the papers corresponding to the topic, ten were chosen.

2.1. VR in robot control

The application described by Ibáñez et al. [3] is an example of a virtual laboratory created in MATLAB. This allowed the students to operate several different robotic arms without purchasing machines and the risk of accidental damage to equipment. According to the authors, such possibilities and immersion of VR technology allow a profound comprehension of robotic issues.

Another example of using VR and AR technologies to teach robotics is the application described by Rukangu et al. [4]. It allows students to connect remotely to the UR-10 robot. Thanks to this, they may complete laboratory tasks during the COVID-19 pandemic; thus, to maintain the appropriate quality of remote education.

VR technology was also used in the application described by Perez et al. [5], which allows users to operate a digital copy of a real-life robotic setup. The created environment may be used for training purposes or for simulating human-robot collaboration with no hazards for operators. According to the survey conducted by the authors, created VR environment is realistic and encourages users to work with robots.

2.2. AR in robot control

AR technology can also be used for educational purposes. An example of such is the educational platform introduced in the paper written by Martin Hernandez-Ordoñez et al. [6]. It consists of two main components: a robot with two degrees of freedom, and an AR application, which enables operating the robot and visualising relevant data. The control algorithms are implemented in Matlab software, and the generated motion instructions are sent directly to the robot. Every segment of the device is equipped with AR markers, which enable scanning it with the camera and calculating configuration. The method thus allows for comprehensive education in the field of manipulator control algorithms, which may be tested on the prepared setup. Moreover, it gives more immersive insight into robot kinematics, as the joint angles may be intuitively monitored thanks to AR.

Another example of using AR technology for teaching robotics is described by Bogosian et al. [7]. The application displays selected industrial manipulators with a corresponding task in augmented reality. With these, the lessons based on various case studies in the fields of architecture, engineering, and construction may be studied. This approach facilitates understanding of the operation purposes of industrial robots and their applications beyond the industry.

AR technology was also used within the application described by Su et al. [8]. It displays industrial robot digital twins in AR. Therefore, its real-live version may be controlled via the application with the HTC Vive controllers motion. The movements registered with the lighthouse sensors are transferred to the application with trajectory planning algorithms. Thanks to this, a user may move the characteristic point of a manipulator with their hands. Due to its mobility and offline capabilities, it is a suitable solution for training in robots control. An online module that allows for the mobilisation of a robot is highly desired for learning about Industry 4.0.

The last example of using AR technology is the application described by Vener [9]. This application is used to control a humanoid robot that performs the task of lifting a load. It displays a digital copy of the robot and essential parameters such as its centre of gravity. In addition, the system provides control of the robot using the buttons available on the user interface and simulation of the expected robot movements. These functions let students understand the dynamics of a humanoid robot easier.

2.3. VR in mobile robotics

According to Zhong, Zheng, and Zhan, the use of VR technology for training in the field of mobile robotics has a similar impact as for industrial robotics [10]. The authors describe involving a virtual environment to operate the IRobotQ3D robot. The study proves that VR technology as an additional part of the educational course brings better results than conventional training with a physical robot only. The educational process carried out within this methodology contributes to reducing the stress level of students and enhancing their design capabilities.

2.4. AR in mobile robotics

Mobile robotics also takes advantage of AR technology. An example of such a case is an application described by Herrera et al. [11]. It is designed to simulate the work of a mobile robot in augmented reality. Thanks to this, the users may get acquainted with control algorithms and robot kinematics. Moreover, the application is accompanied by the feature facilitating a profound understanding of the robot's mechanical structure. Consequently, the described solution allows for a comprehensive presentation of mobile robots regarding their control and mechanics.

Another relevant example is the application described by Mallik et al. [12]. It allows for controlling a real-life mobile robot with a differential drive. To start, a student has to scan a visual tag and then define the model of the robot by locating the centre point of the actual device. Then, the real robot can be controlled by pointing the target point at the screen to build its motion paths. Students using this method found that it was intuitive and helped them understand the topic of robots kinematics. Similarly to the previously described applications, this one increases the efficacy of education in the field of robotics.

2.5. VR in safety

VR technology is also applicable for the training in human-robot cooperation and its safety. One of such applications is described in a paper by Vladimir Kuts [13]. This work presents a system for simulating a real-life factory in virtual reality, including robots, CNC milling machines, and other industrial devices. The person using the application has the opportunity to observe how robots perform their tasks with the deeply immersive human-machine interaction. In addition, the application allows several users to connect to the system simultaneously. Thus, the trainer can run health and safety (OHS) group training for a given robotic setup.

Another example of using VR for OHS training is the application described by Kaarlela [14]. The presented system displays a robotic setup in an immersive VR environment. The workstation model has visually marked safety areas updated during the robot's operation. Additionally, a user can stop or rerun the task performed by the machinery to analyse the movement of the manipulator during the executed instructions. Thanks to these functions, such an approach may be used for complex safety training without a production line stoppage. Therefore, the cost of such actions is significantly decreased, and the risk of not providing customers with the purchased products is mitigated.

2.6. AR in robot construction

AR technology may also be used to explain robots construction and the purposes of operating robotised setups. One such approach is presented by Michaloset al. [15]. As AR technology is only a layer superimposed on the real-life image, it can be used to familiarise students with invisible elements of the machinery. Thus, it allows them to analyse the part without the complication of disassembling devices. Also, thanks to this, students may learn where the selected element is located in the real-life setup, and hence, deeply understand the construction of modern industrial robots. Such an approach may be broadened to applicability in maintenance and service to accelerate repairs and decrease the number of human errors [16].

2.7. Summary of current solutions

Although the previously described solutions may significantly improve the quality of education, they are not free from disadvantages. The main one is that some applications require additional equipment, such as VR goggles or physical robotic devices (e.g., the application described in subsection 2.2). This may limit the solution's usability by increasing its using costs or forcing the students to find specialised institutions providing necessary hardware. Therefore, the main goal of the project described in this paper is to eliminate such difficulties by creating the application involving only the devices already possessed by most of the target group.

3. Case description

This paper presents a solution that requires only an Android device for full functionality. The requirements to be met by a smartphone are included in Table 1. The described application was created to allow student to learn robotics without access to hardware facilities. This is especially important due to the consequent significant cost reduction and the possibility of studying in the real world, anywhere, and with any scenery. An environment like this may simulate potential applications of industrial robots involving real-life objects. Hence, this will encourage users to seek and implement robots in new areas of life.

Tab. 1. Phone requirements

System version	Android 7.0 or higher
Required applications	Google Play Services for AR
Processor	ARMv7
Memory	2GB
Storage	80 MB

Besides the requirements aggregated in the table, the phone must support the ARCore system. Information on whether a particular phone has ARCore support can be found on the page for developers [17]. In addition, Table 2 contains information on tested devices.

This application was created as a component complementary to online courses on robotics. Its aim is to familiarise students with the robotic workstation and teach them possibilities of motion of currently used industrial manipulators. The whole programme was created within the MILAN project.

Tab. 2. Tested devices

Phone model	Processor	RAM memory
Honor 10	HiSilicon Kirin 970	4GB
Xiaomi Redmi Note 8 Pro	Mediatek Helio G90T	6GB
Xiaomi Redmi Note 10 Pro	Qualcomm Snapdragon 732g	6GB
LG G8s	Qualcomm Snapdragon 855	6GB
Samsung Galaxy a71	Qualcomm Snapdragon 730	8GB

3.1. MILAN project

The MILAN project aims to use augmented reality and virtual reality to develop innovative and widely available training materials and tools in the field of automatic control robotics. MILAN training materials are placed on the interactive and freely accessible e-learning platform. This platform provides high-quality training in Advanced Manufacturing, targeted primarily at operators of complex automatic devices and robots, teachers, consultants, and students at technical universities. The MILAN programme includes an e-learning course.

The MILAN project was focused on developing:

1) Case studies overview - collecting information about the most effective technologies and practices used for distance learning, particularly for the field of automatic control and robotics;
2) Curricula of learning blocks;
3) Training content involving virtual reality and augmented reality technologies;
4) Educational platform containing all the necessary elements for online learning;
5) Teaching methodology.

Thanks to the MILAN project, everyone interested in learning automatic control and robotics can have free access to materials published at the e-learning platform, MILAN website, and YouTube channel. In addition, the programme will be enriched with access to the cameras at the robot setups at the ŁUKASIEWICZ Research Network – Industrial Research Institute for Automation and Measurements PIAP and at the University of Technology in Kosice, as well as the remote access to the virtual robotics laboratory. In order to test students' skills in practice, the application described in this paper will be used. All the educational material provided by the MILAN training system can be divided into four main categories:

- Basics of Advanced Manufacturing;
- Automation and Robotics in Advanced Manufacturing;
- ICT in Advanced Manufacturing;
- Occupational Safety and Health.

The point of the MILAN project was to combine the availability and high quality of the courses. Therefore, while choosing an approach to the knowledge presentation and practice, reaching a broad audience was considered [18], [19].

3.2. Description of the robotic station

When using the application, course participants may operate a station for laying down gaskets with the ABB IRB 4600 robot. The industrial manipulator is equipped with a mixing head that pours two-component polyurethane along the gaskets path. As the mixture dries up, it swells and sticks to the base material (e.g., an electric cabinet metal door). The application of the 6-axis robot is as innovative as enabling laying down gaskets at any angle, which may be used for complex geometries (e.g., for 3D-printed custom parts). Moreover, the station allows potential use of the robot for various Advanced Manufacturing tasks with multiple tools. For such an application, both the work tables should be involved. The mentioned work tables also enable simultaneous work of the device and an operator. Thanks to the safety system, these two can work within physical reach.
The developed AR application contains the interactive model of the setup described above. It allows the virtual robot to move within the scope of work, which may be used to check the programmed scope of operation without the risk of collision with the fence. The corresponding 3D model developed in Autodesk Inventor is presented in Figure 1.

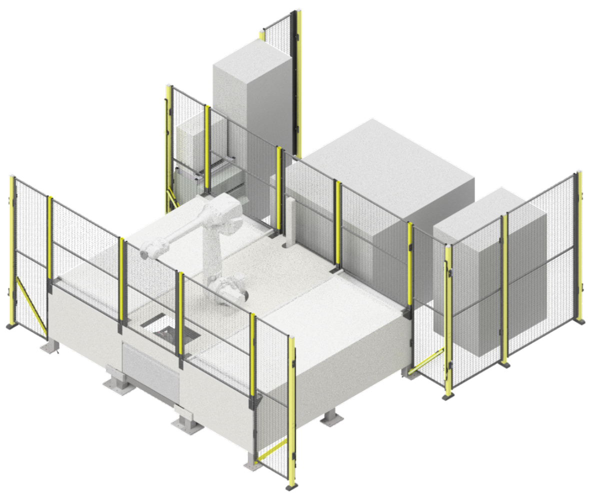

Fig. 1. Station for laying down gaskets

Tab. 3. Information about the robotic setup

Width	5213 mm
Length	5040 mm
Height	max. 3527 mm
Power supply	200-600 V 50-60 Hz

The station presented in Figure 1 contains all the safety measures required for industrial purposes, including fencing and optoelectronic curtains. By using the complete model, participants will learn about industrial robotic stations' construction and their operation principles. Additionally, the presentation of this complex setup may be used to explain the basics of the safety systems or to analyse the required room in the production halls. As a consequence of using AR-based courses, students are not exposed to the risk of injuries while the space and financial costs are decreased. Hence, such an approach to teaching robotics should result in higher availability of high-tech education, staying in line with equal opportunities.

4. Methods of designing the application

The mobile application was prepared for Android phones using the Unity engine (v.2020.1.17f1) with ARCore (v.4.15) and AR Foundation (v.4.1.5) packages. The development of the solution started with pre-processing of the CAD model. This phase is visualised in Figure 2.

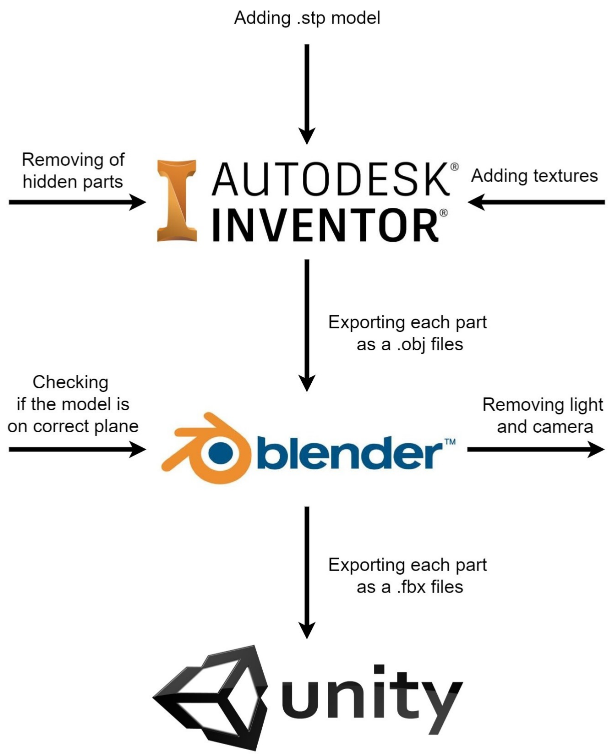

Fig. 2. Diagram of preparing a 3D model

The processed model was ready to be placed in the Unity engine. To obtain an accurate visual of the real-life station, the robot's main dimensions and angular ranges of joints were based on the producer's documentation [20]. Based on these, the Denavit-Hartenberg parameters were introduced [21]. These are shown in Table 4 with the model in Figure 3, while Table 5 contains data on the robot's joints' angular ranges.

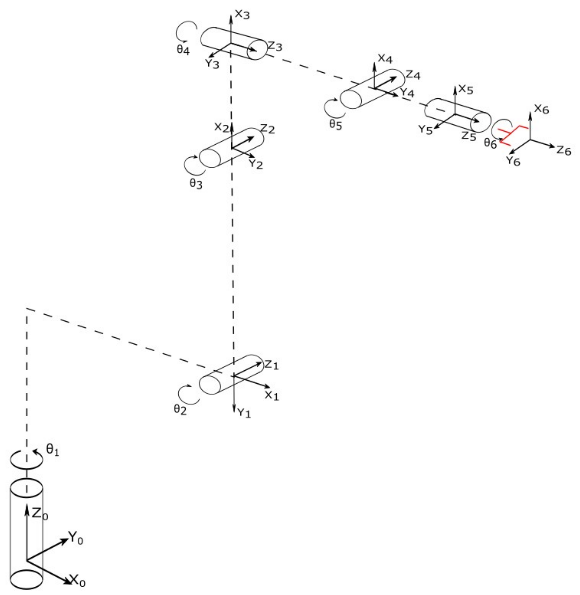

Fig. 3. Denavit-Hartenberg model

Tab. 4. Denavit-Hartenberg parameters

Joint	Ψ_i	Θ_i	D_i	a_i
1	-90	0	495	175
2	0	-90	0	1095
3	-90	0	0	175
4	90	0	1270	0
5	-90	0	0	0
6	0	0	135	0

Tab. 5. Angular reach of the robot's joints

Joint	Range
1	+180° to $-180°$
2	$+150°$ to $-90°$
3	$+75°$ to $-180°$
4	$+400°$ to $-400°$
5	$+125°$ to $-125°$
6	$+400°$ to $-400°$

The Denavit-Hartenberg parameters presented beforehand were introduced to derive the kinematics equations of the ABB IRB 4600 robot. They are being used to calculate the visualised robot's position based on the controls. For deriving the equation, the homogeneous transformation matrix (1) was used.

$$T_i^{i-1}(\Theta_i) = \begin{bmatrix} cos\Theta_i & -cos\Psi_i sin\Theta_i & sin\Psi_i sin\Theta_i & a_i cos\Theta_i \\ sin\Theta_i & cos\Psi_i cos\Theta_i & -sin\Psi_i cos\Theta_i & a_i sin\Theta_i \\ 0 & sin\Psi_i & cos\Psi_i & D_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

The position of the robot's tool characteristic point (TCP) located in the centre of the device's flange is calculated with the transformation matrix according to the formula (2). It depends on the rotation angles in the respective kinematic pairs. Even though the robot has a rigidly assembled mixing head, it is neglected within the computations. An approach like this is caused by the intention of enabling the virtual tools' exchange without modifying the equation itself.

$$T_6^0 = T_1^0 \times T_2^1 \times T_3^2 \times T_4^3 \times T_5^4 \times T_6^5 \times [0\,0\,0\,1]^T \quad (2)$$

To transform the desired position of the tool characteristic point (TCP) into the robot's joint configuration, formula (3) must be solved. The q_i symbol used in this equation is an i-th joint rotation, while x, y and z are transitional position components of the TCP, and a, b, and c are its rotation components regarding x, y and z axes.

$$\left(T_6^0\right)^{-1}[x, y, z, a, b, c]^T = [q_1, q_2, q_3, q_4, q_5, q_6]^T \quad (3)$$

After these stages, the development within the Unity environment was conducted. This contained the following steps:

1) Configuring the augmented reality
   - Adding the AR camera;
   - Adding the indicator appearing at the application start on the detected plane;
   - Implementing the script detecting a flat surface and adding a robotic station in the place of the indicator.
2) Adding the robotic station model
   - Placing and scaling the model in the scene;
   - Adding Cube elements that would be responsible for the motion;
   - Creating a hierarchy of models.
3) Designing the user interface
   - Adding buttons and sliders;
   - Adding labels.
4) Attaching the scripts responsible for the robot's motion
   - Implementing scripts rotating and scaling the model;
   - Implementing scripts moving the robot's subcomponents.
5) Generating a .prefab file and including it as a display object

4.1. AR configuration

The augmented reality configuration was primarily performed with the ARFoundation package. Then, the described initial indicator was designed as the red crosshair placed on the plane estimation of the detected floor. The applied detection functions tracking the position of the model and the light changes are commonly available as pre-made scripts. Nevertheless, the function responsible for placing the object can be described with the following pseudocode:

AR objects and model initialisation
$PoseIsValid \leftarrow false$

function START

Find Raycast Manager

end function

function UPDATE
if Model is not placed and PoseIsValid=true **then**
Place object
end if
Update pose
Update placement indicator
end function

4.2. Adding robotic station model

The critical aspect of adding the model is the accurate initial scaling of the device, so that it corresponds to its actual size while being projected in the augmented environment. Six Cube objects were added to ensure natural motion, with each of them corresponding to one robot's rotary joint. Moreover, the appropriate hierarchy of Cube models and robot components was implemented (see Figure 4).

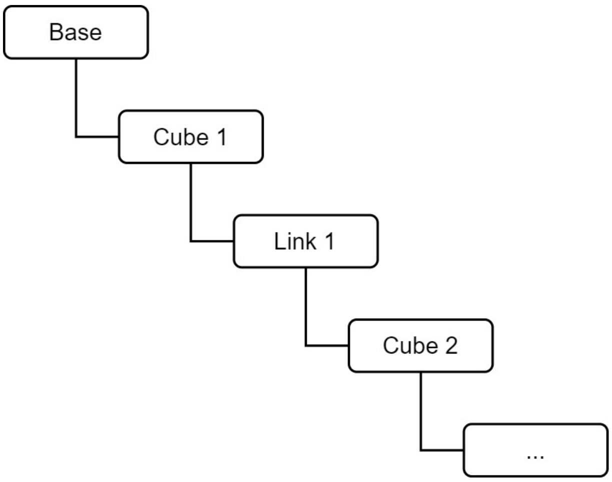

Fig. 4. Models hierarchy

All the files prepared within this stage were placed in an empty GameObject. To enhance the immersion of the AR application, the realism of the object visualisation was increased by modifying the lighting of the Unity engine.

4.3. User interface

The important aspect of educational applications is their user interfaces. They should be relatively simple and intuitive to enable learning without the need for reading the manual. Therefore, all the buttons and sliders were described with labels clearly explaining their functions. In this described solution, the user interface was designed as presented in Figure 5, where:

- A - Station name;
- B - Button to lead the robot to the base pose;
- C - Sliders to rotate and re-scale the entire model;
- D - Buttons to control robot's joints and angular measurements of each.

4.4. Robot motion

The mobile educational application has the functionality of jogging the robot (controlling its every single joint coordinates). Thanks to the hierarchy presented in Figure 4, the motion of one axis affects the position of the following ones. Furthermore, there is a possibility of rotating and scaling the entire station. Thanks to this, the solution enables learning even within the limited space. The robot's motion is controlled with the seven scripts, including:

- Six scripts corresponding to the motion of particular axes of the robot;
- One script responsible for rotating and scaling the model.

Each of the scripts is connected to the corresponding user interface elements and activates the required functions upon click. This is either rotating around the appropriate axis or setting zero rotation for the Base Position button. The last script is connected with two sliders, assigning them to rotating (-180^o to 180^o) and re-scaling (10% to 100% of the real-life size) the entire station. The sliders react with the resolution of $\pm 2^o$.

4.5. .prefab file generation

Afterwards, the scripts had to be attached to the appropriate elements. The ones responsible for the robot's motion were connected with the Cube objects. After assigning these, a .prefab file was generated, and the script responsible for manipulating the entire station was added. The final version of the application is presented in Figure 5.

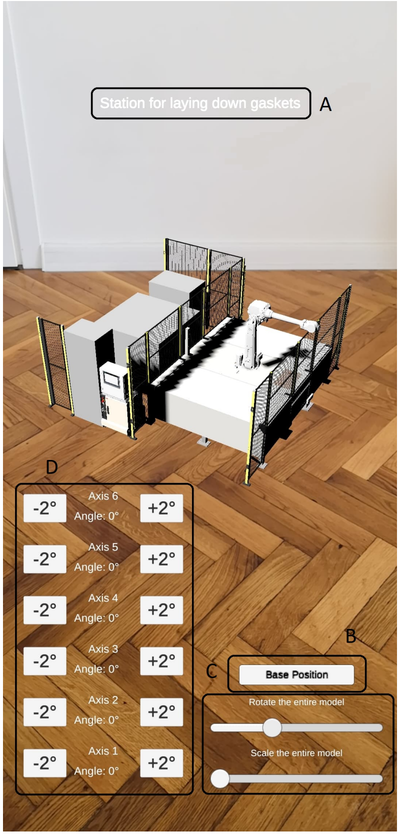

Fig. 5. The application main screen

5. Benefits of using AR/VR

Involving AR technology for education in automatic control and robotics results in the rising availability of courses. This is especially significant for less developed regions or areas located at a distance from specialist training centres or universities. The mentioned impacts are possible due to the following benefits of AR-aided systems:

- Cost reduction;
- Increased quality of education;
- Capability of checking the robot's compatibility with the environment;
- Possible use of the real-life elements for the tasks within the practicals;
- Compliance of the applications with massive open online courses (MOOC) standards and automatic assessments.

5.1. Cost analysis

To perform the cost analysis, solutions available on the market were first reviewed. Depending on the manufacturer, the price of an industrial robot without accessories is estimated as $37,000 on average [22]. The devices equipped with typical manufacturing accessories, such as grippers, tool changers, or sensors cost between $50,000 and $80,00 [23], [24]. The reach, payload, and application are the key factors affecting the cost of the robot. The presented ranges include the robot with only basic accessories only. However, the price of the whole station essential for performing manufacturing processes is approximately $120,000. Moreover, the initial purchase isn't the only cost, as it also generates continuous exploitation costs. These are the expenses related to power and media consumption, maintenance, and upkeep of the machinery. According to Asari, the cost of operating the robotic station for seven years depends on the region of the world [25]. It varies from 15.1% to 42.5% of the total initial purchase price. This means that the total expenses on a device similar to those featured in the app range from $141,000 to $208,000 within its 7-year exploitation period. In comparison, the cost of creating an AR application was also analysed. This cost mainly depends on the application type and range of development. However, in similar cases to the one described in a 2019 paper focusing on marker-less AR application, prices range between $10,000 and $11,500 [26]. As a result, the costs of the AR application and the real-life robotic station are presented in Table 6. As an additional advantage, the application can be installed on unlimited devices. This is a significant superiority to the physical station, which may be operated by only one person at a time. Based on the gathered data, involving AR-based systems for education results in much lower costs, enabling simultaneous training for multiple students at their own pace. Consequently, institutions with limited budgets could improve the quality of their courses at relatively low expenses. On the other hand, the ones that can buy physical devices can save funds thanks to AR applications, e.g., by using fewer robots and offering blended courses.

Tab. 6. Costs comparison [23] - [27]

	Robotic Station	AR Application
Purchase Costs	$120,000	$10,000 - $11,500
Maintenance Costs	$21,000-$88,000	$1,680 - $5,040
Sum of Costs	$141,000 - $208,000	$11,680 - $16,540
Possible Savings	$129,320 - $191,460	

5.2. Impact on education quality

Apart from the economic effects, the quality of education also needs to be assessed. This issue may prove the impact of the suggested teaching methodology. Therefore, an analysis of the impact of AR/VR applications on the efficacy of learning was performed. This analysis is based on the recent works of Li, Fu, and Wang [28]; Alzahrani [29]; and Criollo-C [30]. In all of these papers, the authors found an improvement in the results for the students using AR/VR technologies.

The first study involved substituting learning with a real-life station with a virtual one [28]. This allowed students to work independently instead of sharing one device with a group. After completing the course, students were surveyed. According to the obtained results, 90% of participants stated that an improvement in the quality of the source was noticeable, while 95% said that VR helped them learn faster. In addition, the vast majority of respondents concluded that virtual reality increased their interest in the subject and satisfaction.

The second paper deliberates on the benefits of AR applications introduced at different studying phases and different levels of education [29]. Based on the cited sources, the author concludes that using augmented reality had a positive effect. Involved students described learning as easy, pleasant, and useful compared to traditional methods. Besides, the AR also increased concentration and kept the constant attention of the courses' audiences. Altogether, these factors resulted in a more effective acquisition of new practical skills.

The last paper describes the impact of AR technology on learning in engineering [30]. The study consisted of a comparison for two groups - one learning with the traditional lectures and the second using AR applications during classes. After completing the course, students were asked to describe the course with one adjective. The following were the most common within the outcomes: motivating, easy to use, usable. The impact of AR application on the educational process was also verified through the exam testing students on the acquired knowledge. The group using the AR application obtained, on average, 36.7% higher results than the group using traditional learning. These prove the positive influence of AR technology on increasing interest and the efficacy of acquiring knowledge

The project MILAN, which the presented application was designed for, was published on the Coursevo platform. By the 19th of March 2022, 282 users registered for the course, which saw 320,631 hits.

5.3. Involvement of the real-life environment

In addition to the previously mentioned benefits, AR also allows testing the collaboration of devices with the environment. Moreover, it enables using real-life elements for the courses without the risk of damage. Thanks to this, a given station may be validated in terms of fitting into its intended working space. Moreover, the robot's operational range can be projected for the desired program. Based on this, the environment, including walls and other machinery, may be assessed for possible collisions with the moving elements. The possibility of manipulating the model also allows users to check whether the placement of the devices does not limit the free work of the operators. Such use of the AR application enables learning the best practices within the early phases of designing robotic stations, e.g., cooperation with the environment and employee safety, among others. Moreover, this does not create any risk of harm for humans, like the trials with real-life setups. These crucial aspects are rarely included in the majority of robotics courses.

5.4. Possibility to use the application in massive open online courses

Since the application can be installed on unlimited devices, its use may be easily scaled for MOOCs. These are free online courses available to everyone, during which the student has access to traditional materials such as videos and lectures as well as interactive forums and practicals. Thanks to these courses, students may acquire new knowledge and gain experience at their own pace. Conducted research has proven that MOOCs have a positive impact on student learning. This is mainly due to the availability of detailed tutorials and the constant gathering of data on learners' difficulties and progress [31]. Regarding the analysis from the previous section, a similar course with the AR application could popularise the field of robotics and help already interested students effectively develop their skills without expensive setups.

5.5. Benefit summary

Based on the examples and analyses provided, AR/VR technology significantly reduces the cost of learning while maintaining or even improving the quality of education. This also allows for the explanation of issues that could not be presented during traditional courses. Moreover, the audience of this sort of training could be significantly broadened if AR/VR applications were to be combined with MOOCs. Then, the students would also benefit from learning at their own pace, while the organisers may constantly improve the content based on the gathered data.

6. Summary

6.1. Possible future use

As the described application is designed for Android devices, it can be used for a wide range of purposes.

Its minimum requirement is a compatible smartphone. Therefore, it is suitable for institutions with a low budget and individuals who want to enhance their competencies. This application or similar ones may be deployed directly into the robotics courses targeting these groups. This will allow for enriching theoretical lectures with practical exercises involving a virtual laboratory. Due to the low cost of such a solution, it may contribute to equalising learning opportunities in less developed countries. Using the presented teaching methodology may become a remedy for the lack of access to machinery at the educational institutions. While aiming for long-term increasing learning capabilities, employers' hiring requirements are also expected to rise.

In addition to educational use, similar AR applications can be used for commercial purposes. These include presenting the robotised station design to a customer prior to manufacturing. Thanks to this, the client is aware of the system's visuals and may validate the amount of free space reserved for the machinery. Moreover, this enables improvements at the design stage to meet the customer's needs and expectations without additional expenses on later modifications. Hence, the final solution is fully client-tailored.

6.2. Teaching with the AR application

Assuming that this application is a complete tool, the model approach to the teaching process has to be specified, whether for stationary or remote courses. First, the solution can be used for presenting students with the general industrial robots' design and their motion capabilities.

Then, the kinematics of the industrial manipulators may also be explained with the exercises based on the application. Courses focused on functional and safe designing of robotic workstations may also be organised within the same work-frame. To ensure comprehensive learning capabilities, it would be advantageous to broaden the powers of the application by enabling the loading of custom models. This approach would familiarise users with widely applied solutions and test their mechatronic designs.

6.3. Conclusions

The development of modern smartphones allowed for the implementation of advanced technologies such as augmented reality into multiple fields, including education. However, most solutions involving AR requires the use of professional equipment. This significantly limits the group of people benefiting from this learning methodology.

With the application described in this paper, however, this methodology can reach more people, as it only requires an Android smartphone. Thanks to this accessibility, the application may be used stationary or remotely, which is particularly important during pandemics. Because the application is based on augmented reality, the exercises may include real-life elements, e.g., boards with the paths for the robot's trajectory programming. Moreover, the use of AR allows for training in operating the robot while it is working without a need for experienced staff monitoring safety. Similar applications can also be used to teach about Industry 4.0, which is generally not mentioned in education.

As a result, the use of this presented solution for educational purposes will increase the competencies of students and people working for the industry while equalising learning opportunities. Thus, their skills will be better suited to the constantly expanding scope of robotics activities in their regions. The use of AR for learning automatic control and robotics is expected to rise in popularity, as it has proven to be significantly more effective for many current needs.

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