

IMMERSIVE AR INSTRUCTION FOR PREPARING A MILLING MACHINE IN LABORATORY

Klaudia TOMASZEWSKA*¹, Marcin Robert CZUBASZEK²

¹ Białystok University of Technology, Faculty of Engineering Management; k.tomaszewska@pb.edu.pl,
ORCID: 0000-0002-0233-5707

² Białystok University of Technology, Faculty of Engineering Management; marcin.czubaszek@pb.edu.pl,
ORCID: 0009-0000-2368-0449

* Correspondence author

Purpose: This study aims to develop and evaluate an immersive augmented reality (AR) instruction to support the preparation of a CNC milling machine in a laboratory, addressing the lack of standardized instructions and limited student autonomy.

Design/methodology/approach: The research followed a prototype-based, implementation-experimental approach within a CNC laboratory case study. Key stages of machine preparation were identified, optimal forms of visualization and interaction in AR were defined, and the impact of the AR instruction on student autonomy was evaluated through iterative testing with students of different experience levels.

Findings: The AR instruction increased student autonomy by 150% (from 4/10 to 10/10 engagement), reduced preparation time by 42%, and decreased problem incidents by 90%. Iterative user feedback refined the prototype, improving usability and learning effectiveness.

Research limitations/implications: The study involved a single lab and limited participants (n = 11), affecting generalizability. Future research should explore different machines, larger cohorts, and long-term learning outcomes.

Practical implications: Augmented reality technology support can increase lab efficiency, reduce instructor workload by 80%, and support student self-directed learning. It has applications in technical education and industrial training.

Originality/value: The paper presents a novel AR instruction for CNC machine preparation, incorporating iterative user feedback, and offering practical design guidance for immersive learning in technical education.

Keywords: augmented reality, CNC machine, immersive learning, student autonomy, technical education.

Category of the paper: research paper, case study.

1. Introduction

The dynamic development of production systems and the further increase in their automation and autonomy. While this brings benefits such as cost reduction, increased production capabilities, and product quality, pose a number of challenges for society. More complex devices, employees are required to have a broader range of skills concerning their operation. This also applies to individuals entering the labor market, who should acquire practical skills needed in their profession during their education. Consequently, this necessitates adapting teaching methods and systems to current needs in replicating real-world conditions while maintaining cost efficiency and safety standards. Schools and universities, on one hand, must allow students to interact with various devices, but on the other hand purchasing physical tools such as lathes, machine tools, or transport vehicles involves huge expenses and poses potential threats. Due to this fact, operating such equipment requires constant supervision by the instructor, which means only one person can learn at a time.

Mixed reality technologies can be an important aid in educational processes by enabling the creation of immersive simulations with a high degree of interactivity. Implementing them into the educational process allows for conducting previously unavailable training and provides the opportunity to acquire skills that were previously difficult to obtain in educational institutions.

The following article describes the introduction of the above technology into the teaching process at Białystok University of Technology. It covers activities from the preparation of physical and virtual materials, through conducting classes and comparing their results with the standard use of a physical device, to the evaluation of outcomes. The research problems include the lack of standardized paper instructions in CNC laboratories, the need for continuous instructor assistance during exercises using the device, the varied level of students' competencies in operating CNC machines, and the need to increase students' autonomy in the learning process. The main goal of the research is to develop a methodology for creating an immersive AR instruction for learning how to prepare a CNC milling machine for operation. The specific objectives include the identification of key stages in machine preparation, determining optimal visualization forms in an AR environment, investigating the impact of AR instructions on students' learning autonomy, and developing guidelines for creating virtual instructions in a technical environment.

The study concerns a process that has been practically unexplored in the Polish academic environment: the creation of a comprehensive AR instruction project for a specific CNC machine, focusing on the process of preparing it for operation rather than on machining design. A comparative study was also conducted on the effectiveness of learning with and without experience with the machine, and an iterative methodology for improving augmented reality instructions based on feedback from study participants was applied.

2. Literature review

2.1. Types and definitions of XR technologies

The concepts of virtual (VR), augmented (AR), and mixed reality (MR) are currently considered one of the important technological issues that may affect a range of matters related to the functioning of society, including entertainment, access to culture, private and business communication (Hartmann, Fox, 2021), or industry, for which they are supposed to constitute one of the elements of the so-called Fourth Industrial Revolution (Roberto et al., 2024). All of the mentioned technologies, also collectively referred to as XR, fundamentally concern the use of cybernetics solutions to enhance user capabilities through the constant and immersive creation of digital objects, usually with the use of head-mounted devices (often referred to as goggles), yet they demonstrate significant differences in their scope and purpose of function.

Virtual reality (VR) is based on creating a fully virtual environment, which is displayed directly in front of the eyes of a person wearing goggles that prevent viewing the real surroundings. This makes it possible to fully replicate inaccessible conditions, but functioning with physical objects is practically impossible. Another issue is the manner of movement and interaction, which often requires additional equipment. (Zhao, Ren, Cheah, 2023) Some studies present no fewer than 109 solutions designed to enable users to simulate movement (Lang, 2021). This solution is particularly advantageous when replicating conditions that are difficult to achieve in the location where VR goggles are used (for example, an airplane cockpit, a museum, or a burning warehouse). The first use of this technology dates back to the 1960s (Hartmann, Fox, 2021).

Augmented reality (AR), on the other hand, means overlaying digital elements onto the physical reality surrounding the user. This requires the use of transparent goggles or another medium on which the desired images are displayed. These can include both additional information and various objects. (Zhao, Ren, Cheah, 2023) It can be considered that some of the first examples of applying certain AR solutions were the transparent displays used in combat aviation (so-called HUD, Head-Up Display) (BEASystems), which nowadays are sometimes integrated with goggles, even though it is prototype technology (Pečečnik, Tomažič, Sodnik, 2023). A user utilizing ARs moves in a natural way, while the proper functioning in terms of motion is usually managed by a system in the headset that analyzes the surroundings and the user's behavior.

Mixed reality (MR) represents a direct combination of the virtual and real worlds. In this case, an important aspect is the natural interaction of objects from both categories with each other, which is particularly beneficial when using them for designing new solutions or operating devices. (Wang, Southwick, Robinson, Nitsche, Esch, Mazalek, Welsh, 2024). Occasionally, the term „hybrid reality” is also used to emphasize the connection between virtual and physical objects (Ke, Xiang Zhang, Zuo, 2019). To operate virtual objects, specific gestures are usually

applied, most often mirroring those used with physical devices (for example, „pressing” icons in a virtual interface). Therefore, in some situations, when analyzing theoretical materials, it was necessary to consider the possibility of mixing concepts and to rely on the description of a specific technology or the context of its use.

While the concept of virtual reality is simple and intuitive, the distinction between augmented reality and mixed reality can sometimes be a matter of debate or present challenges. This is visible, among other things, in product descriptions concerning devices, particularly headsets, which can be classified by different distributors as either AR or MR kits. Similarly, some scientific papers do not make a distinction, using the term „AR” to describe solutions that would essentially qualify as MR. At the same time, some theorists consider AR to be a type of MR, placing a greater emphasis on the real world in which digital objects appear (Chang et al., 2022). This arises from a number of similarities between the described technologies, both in terms of visually similar devices (head-mounted displays) and the use of digital elements such as real-time simulation, 3D graphics, human-machine integration technologies. At the same time, the main differences should be taken into account, including those related to hardware requirements, level of immersion, and the interaction itself (Ke, Xiang Zhang, Zuo, 2019).

Thus, the collective term “XR” (extended reality) is often used, which is intended to encompass the aforementioned technologies. (Crogman, Cano, Pacheco, Sonawane, Boroon, 2025) However, it is mainly used in the scientific sphere rather than in the media or commercial sectors. In the further part of the article, the terms VR, AR, MR, and XR and their equivalents will be used in accordance with the definitions described above.

2.2. Platforms for creating industrial AR instructions

In addition to hardware devices, proper functioning of the goggles requires the use of appropriate software and programs with the desired functionalities. These are the ones responsible for the direct user experience. They also allow for the actual use of the equipment, including for educational purposes and for creating instructions. A few examples are presented below.

A product in this category from PTC is the Vuforia program, specifically designed for creating virtual instructions for service and manufacturing companies. The environment also supports mobile devices, including telecommunication devices, as well as augmented reality headsets such as Magic Leap, Microsoft HoloLens 2, and RealWear. The Vuforia Studio component allows for the development of models directly imported from CAD environments. Furthermore, using the program does not require specialized programming knowledge (no-code/low-code). An important element is also the tool for remote support or collaboration using AR technology called Vuforia Chalk. It is intended to make it easier to solve complex problems without the need for the physical presence of consulting or technical teams (PTC).

Another example is the Dynamics 365 Guides application offered by Microsoft, which is more broadly connected, among others, with Microsoft Dynamics 365 Field Service, and is intended to enable the seamless transfer of information and instructions to 'field' employees. The application itself allows for the intuitive preparation of instructions, without requiring the use of specialized notations, for tasks such as the operation and maintenance of a given device. Some actions are performed using goggles, which allows for controlling how the content is presented to the end user. The process itself is divided into steps and allows for the addition of text and multimedia files, as well as built-in shapes (Microsoft).

LightGuide from the company of the same name is another example of an environment for creating instructions in the form of augmented reality, intended for various applications, including production, training, and warehouse management. The main benefit highlighted here is the reduction of reliance on the operator's memory, thereby increasing so-called 'cognitive ergonomics.' The created instructions can be integrated with various types of equipment and mobile devices. According to the manufacturer, the use of this solution reduces training time by 75% (LightGuide).

Another application is Manifest by Taqtile, Inc. In this case, in addition to the functions of creating and generating instructions intended for use in augmented reality, the tool is supported by components utilizing artificial intelligence, thereby replacing some actions with task description inputs (so-called Prompts). In addition, this technology is also characterized by a no-code approach and is intended to be user-friendly and easy to use (Taqtile).

Eassemble, in turn, is intended largely for use on traditional mobile devices. It allows for creating simple instructions and generating virtual models of real components in their actual environment. Unlike the previously mentioned tools, here the user is primarily the end customer, often without production qualifications (Eassemble).

2.3. Applications in industry and education

Theoretically, the use of AR- and MR-based systems is supposed to offer a number of benefits, including reducing the cost of training a new employee (by up to 50%) and increasing their productivity (by up to 40%) (PTC). The introduction of Vuzix AR Smart Glasses with special software by Airbus within a month led to a sixfold acceleration in the assembly of cabin seats, while Lockheed Martin, in collaboration with Ngrain, increased the production rate of F-35 aircraft by 30% and minimized number of errors (Airforce Technology). Other examples of companies using AR include STERIC (reducing errors and improving the efficiency of industrial dishwashers), Howder (development of instructions for users repairing equipment based on three-dimensional CAD models), Vectrona (accelerating training and enabling remote participation), Peterbilt (increasing service efficiency and accuracy), and Volvo (improving the „quick response” system for failures) (PTC). At the same time, various types of limitations and barriers hinder the widespread adoption of augmented and mixed reality technologies in this industry. These include both internal factors within

companies, such as a lack of understanding of the significance and benefits of implementing headsets, insufficient funding, and the time resources required for implementation, as well as external factors related to the relatively low software quality in terms of lacking proper functions, difficulties in use, or failure to meet industrial requirements (Roberto et al., 2024).

Examples of industrial use of augmented and mixed reality technologies indicate their important role in employee training. This is connected with one of the proposed areas of its implementation, namely education. The main advantages in this regard include the possibility of using immersive simulations that realistically replicate various objects or environments while ensuring user safety, reducing costs due to the lack of need for physical objects, and a wide range of situations that can be presented. They also enhance the possibilities for remote or hybrid learning and increase the attractiveness of training sessions (Al-Ansi, Jaboob, Garad, Al-Ansi, 2023).

An important aspect thus becomes identifying the possibilities of implementing XR solutions in the context of education at various stages, including during technical studies. This primarily concerns so-called experiential or experimental learning, in which the trainee has the opportunity to directly encounter or observe a given phenomenon in natural conditions. Classic examples of tools used in this teaching method include conducting experiments, study visits, workshops, trips, and, more recently, the introduction of XR technology (Crogman, Cano, Pacheco, Sonawane, Boroon, 2025). The first attempts to use it date back to the decade 1989-1999, when its potential in the fields of physical sciences and medicine was being tested. In subsequent years, along with the development of technology, including both the VR headset kits themselves as well as broader computer science and cybernetics, the possibilities for implementation increased (Sala, 2021). The basic advantages include the ability to enhance immersion, present 3D models in a realistic way, increase engagement, solve more realistic problems, and offer extensive visualization possibilities for certain concepts that are not accessible under normal conditions (Chang et al., 2022; Abdullah et al., 2022). Essentially, the number of studies conducted in this area is increasing, which is reflected in a similar trend in publications on the subject (Koumpouros, 2024). To date, research has relatively rarely focused on the use of XR technology among students of technical fields, although it has been widely applied in the sciences (Abdullah et al., 2022), primarily for visualizing various issues. Most studies have focused on comparing the effects of standard instructions with AR-based instructions (Chang et al., 2022). Due to the potential of using AR and MR glasses in production and the importance of a properly trained employee, it is considered appropriate to conduct further research in this area.

3. Research methodology

The conducted study was qualitative with quantitative elements and was based on an iterative approach. It was carried out in the form of a case study of the CNC laboratory at the Faculty of Management Engineering at Bialystok University of Technology. This methodological approach is widely used in research on educational technologies, where iterative improvement of the prototype based on continuous feedback from end users is crucial. The research process involved the systematic enhancement of the immersive AR instruction prototype based on observations, interviews, and tests with the participation of the instructor and students with varying levels of experience.

The study utilized Microsoft HoloLens 2 goggles, which are mixed reality devices combining features of augmented reality with the ability to interact with virtual objects in a physical environment. The choice was based on the device's advanced technical capabilities and the availability of a dedicated platform for creating industrial and educational instructions in an AR environment. The goggles allow for gesture control without the need for physical manipulators, provide stable head mounting, and offer a battery life of 2-3 hours.

A total of eleven people participated in the study, divided into three categories differing in skill level. The first category consisted of an expert a research staff member who conducts classes in the CNC laboratory and has many years of experience. His role was to verify the instructional content for accuracy and identify key moments where students most commonly make mistakes. The second group consisted of four students from technical fields with previous experience operating CNC milling machines. The third and largest group comprised six students with no prior experience operating CNC milling machines, who represented the target audience of the instructions.

Demographic characteristics such as age and gender were not collected or analyzed, as the focus of the study was on the relationship between prior technical experience and the effectiveness of AR instructions. All participants were enrolled in the same engineering program and shared similar educational backgrounds in technical subjects, which provided a relatively homogeneous sample in terms of relevant technical knowledge and spatial reasoning abilities. The decision not to analyze demographic variables was justified by the study's specific focus on experiential learning and skill acquisition, where prior hands-on experience with CNC machines was identified as the primary variable of interest.

In the research process, methodological triangulation was applied. The primary method was participant observation, conducted both during the prototype development stage and during its practical use. Observations were systematically documented in the form of meeting notes. Complementing the observations were semi-structured interviews conducted with participants immediately after the completion of each testing session. Additionally, participants completed satisfaction questionnaires. All qualitative data were supplemented with quantitative

measurements, including the time taken to complete individual steps of the instructions, the number of errors made, and the frequency of the facilitator's interventions. The total time required for each participant to complete the entire machine preparation process was recorded using a digital stopwatch. Timing began when the participant put on the HoloLens 2 headset and ended when they successfully completed the final step of the preparation sequence. An independent observer (a research assistant trained in the measurement protocol) was responsible for all time measurements to ensure consistency and objectivity across all testing sessions. The observer remained at a fixed position in the laboratory with a clear view of the participant and the milling machine but did not interact with participants during the task execution unless a critical safety issue arose. Throughout each testing session, the observer maintained field notes documenting participants' behaviors, verbal expressions, and non-verbal cues indicating understanding, confusion, confidence, or frustration. These observations were particularly valuable for identifying interface ergonomics issues and usability problems that quantitative metrics alone might not capture. After each stage of testing, feedback from participants was systematically analyzed to identify recurring themes and specific areas requiring improvement. This feedback directly informed the modifications made in subsequent prototype iterations, following an agile development approach that prioritized user-centered design.

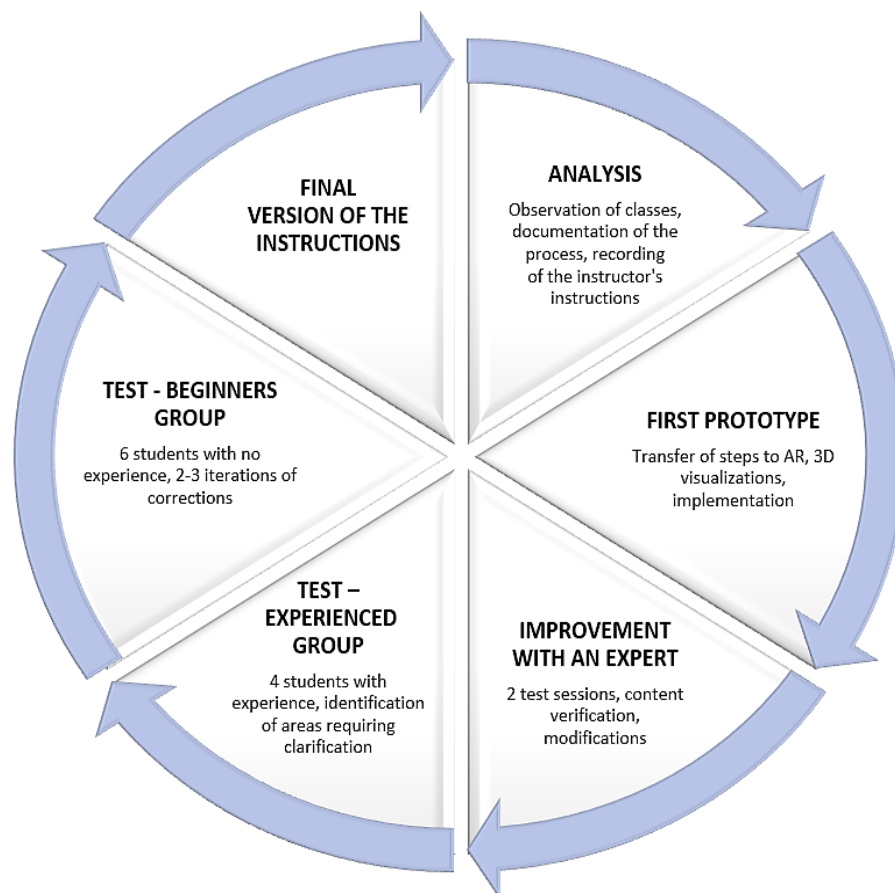


Figure 1. Research study design.

Source: own study.

The study was divided into five main stages (Figure 1). Stage 1 (needs analysis) was exploratory in nature – laboratory classes were observed, and the most common problems encountered by students were identified. Stage 2 involved developing the first prototype of AR instructions with three-dimensional visualizations of key elements of the milling machine. Stage 3 constituted an iterative refinement phase in collaboration with an expert (2-3 test sessions). Stage 4 included testing with a group of four experienced students, which allowed for the identification of information redundancies and interface ergonomics issues. Stage 5 involved testing with a group of six novices – this phase was validation-oriented and enabled the implementation of the final iterations of prototype improvements.

4. Research results

The iterative process of refining AR instructions yielded a number of significant observations regarding the design of immersive interfaces in the context of technical education. Each stage of testing revealed new aspects of user interaction with the augmented reality environment, which required modifications both in terms of the content and the way information was presented.

4.1. From visual chaos to clarity - the evolution of the first iteration

The preliminary version of the AR instructions, although substantively correct and complete, proved insufficient for students without prior experience to independently carry out the full process of preparing the milling machine. During initial tests with an expert and a group of experienced students, fundamental problems related to the organization of visual information and the structure of the message emerged. The study leader noted that some activities, which in the traditional teaching process were conveyed orally with the possibility of immediate demonstration, required a much more precise contextual description in the instructions, as well as support in the form of video materials. Particularly problematic were the procedures related to setting the tool at the zero points for individual axes, which required not only understanding the theoretical concept but also precise execution of the sequence of movements. During the interview, it was noted that „The instruction is logical, but a student without experience will not know how to set the tool at the zero points. It would be good to show this in a video – then everyone would understand what it is about”.

An equally significant problem turned out to be the excess of visual elements in individual steps of the instructions, which led to confusion. Students from the experienced group reported that too many arrows, labels, and photos displayed simultaneously caused difficulties in identifying the most important information. One participant expressed it as follows: “There were so many arrows on one screen that I didn’t know where to look first”. Additionally,

some of the video materials duplicated content already present in the static images, leading to informational redundancy. Another student noted, „The video and photos showed the same thing – I wasted time trying to figure out what was more important”.

In response to the identified issues, a series of modifications were introduced to simplify the interface and improve the readability of the instructions. The number of visual elements displayed simultaneously was reduced. Individual photos were replaced with collages illustrating sequences of actions in a single view (example in Figure 2 and Figure 3).

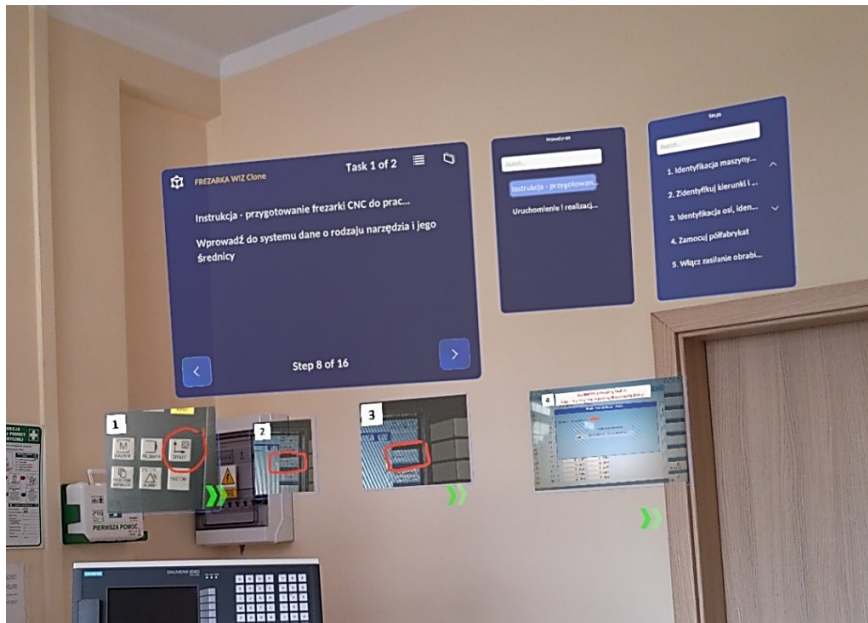


Figure 2. Example of action sequence before modifications.

Source: own study.

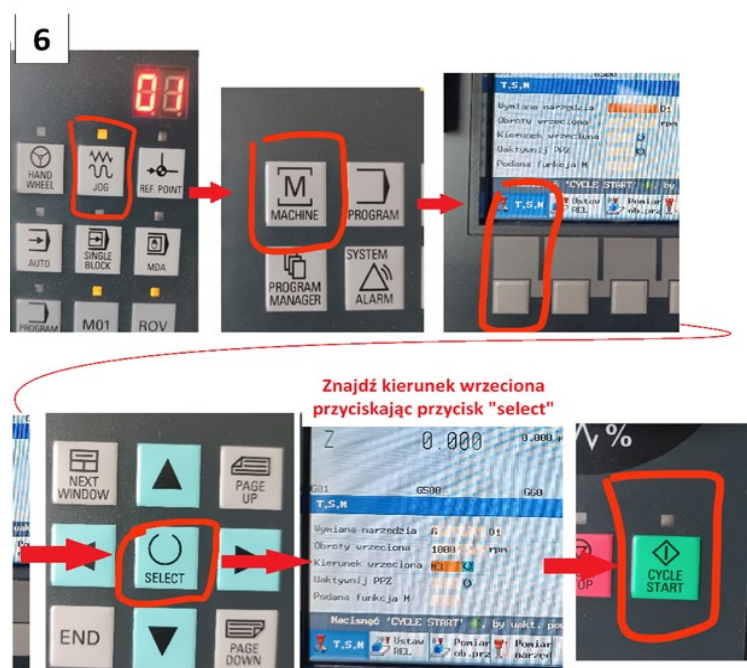


Figure 3. Example of action sequence after modifications.

Source: own study.

Additional textual descriptions explaining key technical concepts have also been introduced. Special attention was paid to standardizing the color scheme: red arrows for warnings, green for subsequent steps, blue for contextual information.

4.2. Interface ergonomics as the key to user autonomy

Despite significant improvements introduced after the first iteration, subsequent tests revealed issues related to the ergonomics of the AR interface and users' visual perception. Some students reported difficulties reading small graphical elements, despite the automatic calibration of the HoloLens 2 goggles. The problem was particularly pronounced in situations where participants slightly shifted the goggles during use. One student described it as follows: „When my glasses were slightly shifted, I couldn't see the texts clearly. After enlarging the images and moving them above the cockpit, it became much easier”.

Another significant problem turned out to be the spatial arrangement of the interface elements in relation to the work area. In the second version of the instructions, the AR interface was placed at some distance from the milling machine, which required users to frequently shift their gaze between the machine and the virtual instructions. Additionally, there was a lack of precise markings on the buttons and control elements on the milling machine's cockpit, which forced students to identify the correct controllers themselves based on textual descriptions.

In the third iteration of the prototype, comprehensive changes were introduced aimed at optimizing interface ergonomics. Most graphics were significantly enlarged. The AR interface was positioned directly above the milling machine cockpit, so that it is within the user's natural field of view during operation. A system of clear markings in the form of red frames was implemented, applied directly to the buttons and control elements in the actual cockpit. For the most complex procedures, dedicated demonstration videos were added, showing precise hand movements and the desired end result.

The effects of the implemented changes exceeded expectations. In the final version of the instructions, all participants in the novice group were able to independently prepare the machine for operation using only the AR instructions, without any intervention from the instructor. The average machine preparation time was reduced by 42% compared to the first iteration, and the number of errors committed dropped to almost zero. As one participant stated: „When the buttons were marked in the pictures, everything became clear”. Another added: „I no longer had to ask the instructor; I would just go back to the previous step if I missed something”. Particularly interesting was the comment from a student: „Now it's more like a game—you just go step by step and everything works”.

4.3. Quantitative analysis of iteration effects

The machine preparation process was decomposed into 15 distinct steps (S1-S15), each representing a critical action required to safely and correctly prepare the CNC milling machine for operation. These steps were defined based on the standard operating procedures used in the laboratory and validated by the expert instructor. Systematic measurement of the execution time of individual instruction steps, as well as the recording of all problem incidents, allowed for an objective assessment of progress in successive prototype iterations. Problem incidents were operationally defined as any occurrence requiring external intervention or correction, including: (1) explicit instructor intervention when a student performed an incorrect action or was unable to proceed, (2) student errors requiring correction (e.g., selecting wrong machine components, incorrect sequence of operations), (3) prolonged hesitation exceeding 30 seconds at a single step, and (4) safety-related stops initiated by the instructor or student (see Table 1).

Table 1.

Number of problem incidents in key steps of the instructions

Step	Stage 1	Stage 2	Stage 3
S1	1	0	0
S2	1	0	0
S3	3	0	0
S4	3	1	0
S5	2	0	0
S6	2	1	0
S7	4	0	0
S8	6	0	0
S9	9	0	1
S10	7	1	0
S11	3	1	0
S12	3	0	0
S13	1	1	0
S14	3	0	0
S15	1	0	0
Total	49	5	1
Reduction compared to stage I	-	90%	98%

Source: own study.

Each step builds upon the previous ones, creating a logical sequence that students must complete in order to successfully prepare the machine for actual machining operations.

In the first stage of testing, a total of 49 problem incidents were recorded. The most problematic steps turned out to be those related to setting zero points and operating the cockpit (S7-S10), where a total of 26 incidents were recorded (53% of all problems). This distribution indicated that the main difficulties arose when transitioning from simple mechanical tasks to more complex procedures requiring an understanding of technical concepts and precise execution of movement sequences.

In the second stage, the number of incidents dropped drastically to just 5, representing a 90% reduction. The incidents in this stage were of a different nature – they did not result from misunderstanding the instructions, but rather from participants being overly cautious and asking for confirmation that they had performed a step correctly, even though they had actually completed it properly.

In the third iteration, nearly complete elimination of problems was achieved, with only one incident recorded at step 9, related to a temporary technical issue with the calibration of the goggles for one of the participants. The remaining participants completed all steps without any intervention from the facilitator.

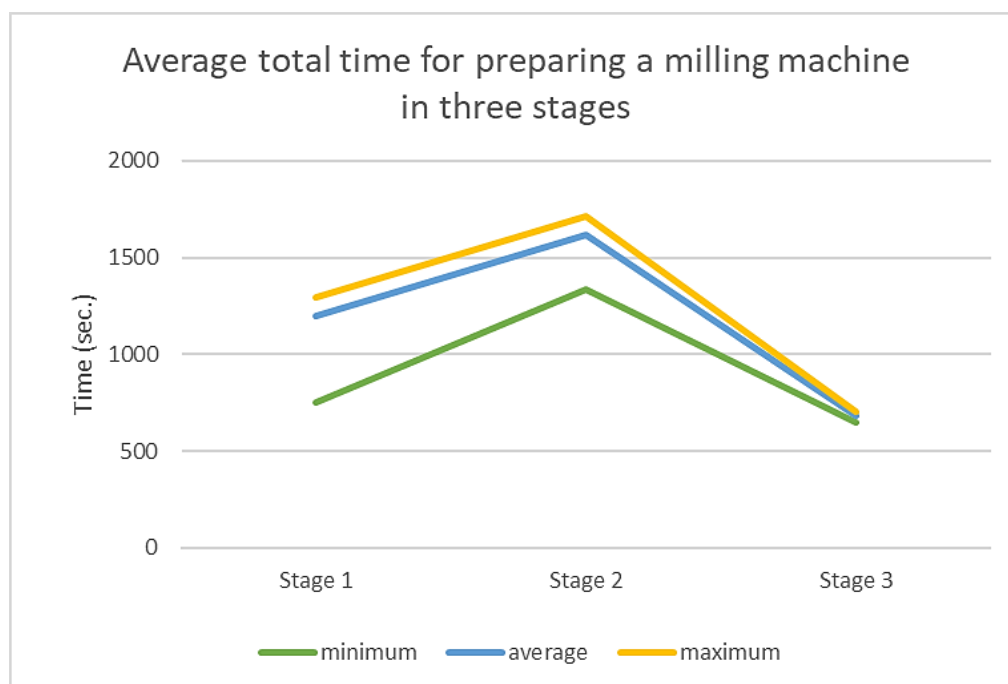


Figure 4. Average total preparation time of the CNC milling machine at different stages of the study.

Source: own study.

The graph of average total time (Figure 4) clearly shows the paradox of the second stage, where the time increased by 14% compared to the first stage, followed by a drastic decrease in the third stage, achieving a 42% reduction relative to the starting point. This apparent paradox, which is longer completion time despite improved instructional materials, reflects a shift from superficial task execution to deeper conceptual engagement.

Behavioral observations from Stage 2 revealed that participants spent more time watching demonstration videos, often replaying them multiple times, and carefully studying the newly added contextual text explanations. Verbal think-aloud data further showed that participants were actively reasoning about why specific procedures were required rather than simply following visual cues. For example, one participant noted: “Oh, so the reference point establishes where the machine thinks it is”. Such engagement contrasts sharply with Stage 1 behavior, where participants relied on prior experience, frequently making errors that required correction. The additional time in Stage 2 thus represented productive cognitive effort rather

than inefficiency, ultimately leading to the substantial performance improvement observed in Stage 3.

Although advanced cognitive load measures (e.g., eye-tracking) were not employed, convergent evidence from observer notes, participant comments, and performance data strongly supports this interpretation. Future research incorporating these methods could further clarify how instructional design fosters optimal balances between immediate task completion and long-term understanding.

5. Discussion

5.1. Transformation of the teaching model - from dependence to autonomy

One of the most significant effects of introducing AR instructions was a fundamental change in the teaching model from the traditional one, based on continuous guidance from the instructor, to an autonomous model in which the student independently controls the pace and manner of completing the task.

Table 2.

The evolution of the teaching model in successive stages

Stage	Commitment	Level of autonomy
Stage I	4/10	Continuous assistance from the instructor, pointing to buttons
Stage II	7/10	Periodic questions to the instructor, independent completion of most tasks
Stage III	10/10	Complete independence, instructor acting as an observer

Source: own study.

In the first stage, students performed tasks only after receiving explicit instructions from the instructor, often waiting for a physical indication of the correct machine component. The instructor was forced to continuously monitor each participant, which practically made it impossible to work with a larger number of students simultaneously. In the third stage, all participants were able to prepare the milling machine for work independently. The instructor acted as an observer and was present only for safety reasons. This transformation leads to increased laboratory throughput and a reduction of the instructor's workload by approximately 80%.

5.2. The advantage of AR instructions over traditional methods

Table 3.

Comparison of the traditional method with the AR instruction

Teaching aspect	Traditional method	AR instruction	Effects of change
Work autonomy	Small, constant supervision required	Big, the student can work independently	The ability for many students to work simultaneously
Learning pace	Low, the need to wait for the instructor's availability	Adapted to the student, work at a pace depending on the student's abilities	Better alignment with the student
Standardization	Small, dependent instructions of the instructor	High, standardized instructions for each participant	Standardization of the educational process
The number of students performing actions simultaneously	Limited by the number of machines and instructors (usually 1)	Limited by the number of AR devices	A larger number of students performing tasks simultaneously (provided there are more goggles)
Ability to return to instructions	Based on inquiry - the necessity of asking the instructor a question, the repeated instruction will usually differ from the original	Flexible – the student can go back to previous steps at any time	Increase in the student's ability to self-improve and correct mistakes
Instructor's workload	High, requiring constant supervision and providing additional instructions	Low, supervision over the group and possibly explaining problems	The ability to provide more answers in ambiguous situations
Student comfort and engagement	Low, fear of being judged by the group when asking questions, waiting time for the opportunity to start working encourages distraction	High, individual work and comfortable learning from mistakes, little or no waiting time for the opportunity to act	Greater comfort and student engagement positively affect their learning.

Source: own study.

The comparison reveals fundamental differences that impact the effectiveness of the teaching process. In the traditional method, the complete lack of standardization meant that each student received a slightly different version of instructions, depending on the current knowledge of the instructor, their fatigue, or time pressure. The student had no opportunity to return to earlier stages of the process without seeking help again, which often caused feelings of awkwardness and fear of being judged as less capable.

In contrast, the AR instruction in its final version provides full standardization of the process for all students, eliminating the human factor as a source of variability in teaching quality. The ability to freely go back and repeat steps is a fundamental advantage – a student can return to a previous stage, review the instructions again, and correct their actions without any social pressure. Simultaneous support for multiple stations means that theoretically an unlimited number of students can use the AR instruction at the same time, which radically increases the laboratory's throughput.

5.3. Key success factors in AR instruction design

The analysis of the iterative process identified five key factors that determine the effectiveness of AR instructions in technical education. These include multimodal support, which involves skillfully combining different forms of communication tailored to the specifics of individual tasks. Text descriptions are essential for explaining theoretical concepts, static images are effective for presenting target positions, collages are useful for illustrating step sequences, and video materials provide the most comprehensive form of communication for complex procedures requiring the simultaneous execution of several coordinated movements; **contextual placement** of content, that is, the positioning of AR interface elements in physical space, which minimizes the user's cognitive load. Placing key instructional elements directly above the milling machine cockpit radically shortened task completion time. Overlaying labels directly onto the physical machine components eliminates the need for mentally mapping information from the instructions to the real objects; **visual consistency**, in the form of appropriate use of graphic elements, color schemes, and information hierarchy. Users quickly learn the meaning of individual visual elements if they are applied consistently. A color-coding system (red - warnings, green - next steps, blue - contextual information) allows for intuitive navigation through the instructions; **progressive simplification**, that is, the systematic elimination of unnecessary visual and informational elements. An excess of visual elements leads to perceptual chaos and increases the time needed to process information. The principle of „less is more” has proven fundamental for designing effective AR interfaces, where visual space is limited, and the user must simultaneously process information from both the physical and virtual reality; **feedback loops**, that is, mechanisms for confirming the completion of steps as well as the possibility of self-monitoring and self-correction. Adding photos showing the final effect of each step allowed users to independently verify the correctness of the actions performed. The ability to freely go back to previous steps supports the learning process through trial and error, which is natural for humans.

Research on the application of augmented reality technology in training and education is not a domain of recent years. The issues of implementing AR in higher education and employee training have been considered for a relatively long time; however, they often remained theoretical or developmental proposals due to costs and imperfections of the devices themselves (Lee, 2012). Technological development in many respects has solved this problem, making more accurate, as well as accessible and convenient, tools available. A key issue is to compare and assess to what extent the use of augmented reality technology enhances (or does not enhance) the knowledge acquisition process. Between 2014 and 2023, there was a dynamic increase (except for the year 2016) regarding the number of publications on empirical studies concerning higher education classes using virtual instructions, reaching over 30 in the record year of 2020. Furthermore, the vast majority of analyses were empirical in nature (Li, Luo, Chen, Wang, Yin, Zhang, 2025). Research may focus on experiences related to the use of

goggles (Saez-Lopes, Cozar-Gutierrez, Gonzalez-Calero, Corrasco, 2020); however, introducing a comparative analysis between traditional methods and those utilizing augmented reality technology represents a very important direction of research that makes results more objective. An example of this is the comparison of test results of student groups preparing either without or with AR technology, where in the latter case, there was a significant improvement not only in performance but also in student engagement (Tian, Ironsi, 2025). Another example was the implementation of augmented reality techniques for learning 3D object design in a virtual environment, where an improvement in pass rates of over 20 percentage points was also observed (Rizov, Rizova, 2015).

The originality of this study is evident in several aspects. First, the detailed documentation of the design process itself and the iterative refinement of the AR instructions provides valuable guidance for future designers. Second, it is one of the few studies conducted in the Polish academic environment. Third, the focus on the process of preparing the machine for work, rather than on programming or the machining process itself, fills a gap in the literature. Fourth, the use of a mixed-methods approach, combining qualitative and quantitative methods, allowed for obtaining both deep descriptions of user experiences and objective measures of effectiveness.

5.4. Study limitations and directions for future research

This study has a number of limitations that should be considered when interpreting the results. The first limitation is the relatively small sample size ($n = 11$), which does not allow for advanced statistical analyses or generalization of the findings to larger populations. Some students participated in subsequent stages of the study, introducing a potential learning effect independent of the AR instruction itself. The second limitation is the focus on a single specific machine in one laboratory, meaning that directly transferring the solution to a different type of machine would require significant adaptations. The third limitation is the lack of long-term measurement of knowledge retention – the study did not assess how long students retain the ability to independently set up the machine after a week, a month, or a semester following the training. Additional limitations are hardware issues related to the HoloLens goggles (overheating, limited battery life, weight), controlled laboratory conditions that differ from real industrial conditions, and the lack of a control group learning using traditional methods during the same period.

The identified limitations indicate directions for future research:

- Study on a larger sample with a control group and participant randomization.
- Long-term analysis of knowledge retention (tests after a week, a month, a semester).
- Analysis of skill transfer to other types of CNC machines.
- Expansion of instructional content to include machining programming elements.
- Testing in real industrial conditions with typical stressors.

- Application of advanced methods for cognitive load analysis.
- International comparative studies in different cultural contexts.

6. Summary

The conducted study provides compelling evidence that immersive augmented reality instructions can effectively support the learning process for operating complex technical devices in an academic environment. The application of an iterative approach involving end-users allowed for a 42% reduction in machine setup time, a 90% decrease in the number of problematic incidents, and an increase in student autonomy from 4/10 to 10/10 engagement points.

The most important conclusion is the observation that iterative design involving end users is necessary to create an effective AR instruction. None of the prototype versions reached a satisfactory level of functionality without multiple tests and modifications based on observations of real-world usage. This conclusion has significant practical implications for institutions and companies planning to implement AR technology – they must account for the time and resources required for the testing and refinement phase in their budgets and schedules.

The second key conclusion is a radical change in the teaching model resulting from the use of AR instructions – a shift from students being fully dependent on the continuous assistance of the instructor to complete autonomy in performing the task. The instructor ceases to be the source of procedural knowledge and becomes a designer of educational experiences and a mentor. This change in role aligns with the principles of contemporary pedagogy, yet the implementation of these principles in technical education has so far been limited due to the need for direct demonstration of manual activities.

The third significant conclusion is the fundamental importance of video materials for the effectiveness of AR instructions in the case of complex tasks requiring spatial precision and sequential movements. Static images proved insufficient for illustrating dynamic procedures. At the same time, overusing video materials can lead to longer task completion times, so designers must make a conscious choice of the form of communication.

The fourth conclusion is the particular importance of AR interface ergonomics – seemingly minor design decisions regarding the size of graphical elements, their placement relative to the workspace, or device calibration have a direct and significant impact on the usability of the entire solution. Even an instruction that is factually correct can be nonfunctional if the user has difficulty visually perceiving the interface elements.

The fifth conclusion is the phenomenon of spontaneous gamification of the learning process, where students begin to perceive working with an AR instruction as a form of interactive game. In the case of the study, gamification was not intentionally designed but arose

naturally from the characteristics of the AR interface, which structures the task into clearly defined steps, provides immediate visual feedback, and allows progress tracking.

The final conclusion is the importance of the 'less is more' principle in AR interface design. An effective instruction does not consist of maximizing the amount of presented information, but of consciously selecting the appropriate form of communication and eliminating all unnecessary or redundant elements. In the context of AR, this principle becomes particularly significant due to the limited visual space and the need to simultaneously process information from both the physical and virtual reality.

In summary, the study confirms the significant potential of AR technology in higher education, while also revealing that designing effective instructions requires an iterative approach, special attention to interface ergonomics, and a conscious selection of delivery methods. AR technology is not a universal solution and comes with technological limitations and implementation costs; however, in appropriate contexts and with proper design, it can be a valuable complement to traditional teaching methods, opening up new possibilities for personalizing the educational process and supporting learners' autonomy.

Acknowledgements

This research was funded by a grant from the Ministry of Education and Science received by the Bialystok University of Technology. (grant number WZ/WIZ-INZ/4/2025). We would like to sincerely thank Dr Eng. Krzysztof Łukaszewicz for participating in the study and generously sharing his knowledge and experience, which greatly contributed to and enriched the results of this project.

References

1. Abdullah, N., Baskaran, V., Mustafa, Z., Ali, S., Zaini, S. (2022). Augmented Reality: The Effect in Students' Achievement, Satisfaction and Interest in Science Education. *International Journal of Learning Teaching and Educational Research*. Vol. 21, Iss. 5, pp. 326-350, doi: 10.26803/ijlter.21.5.17
2. Al-Ansi, A., Jaboob, M., Garad, A., Al-Ansi A. (2023). Analyzing augmented reality (AR) and virtual reality (VR) recent development in education. *Social Sciences & Humanities Open*, Vol. 8, Iss. 1, pp. 100532-100542, doi: <https://doi.org/10.1016/j.ssaho.2023.100532>
3. *AR and VR's role in aviation*. Retrieved from: <https://www.airforce-technology.com/analyst-comment/ar-vr-role-aviation/?cf-view>, 19.09.2025.

4. Chang, H.-Y., Binali, T., Liang, J.-C., Chiou, G.-L., Cheng, K.-H., Lee, S., Tsai, C.-C. (2022). Ten years of augmented reality in education: A meta-analysis of (quasi-) experimental studies to investigate the impact. *Computers & Education, Vol. 191*, pp. 104641-104665, doi: <https://doi.org/10.1016/j.compedu.2022.104641>
5. Crogman, H., Cano, V., Pacheco, E., Sonawane, R., Boroon, R. (2025). Virtual Reality, Augmented Reality, and Mixed Reality in Experiential Learning: Transforming Educational Paradigms. *Educ. Sci., Vol. 15(3)*, 303, doi: <https://doi.org/10.3390/educsci15030303>
6. Easemble. *Step into the Future with Augmented Reality (AR) Feature*. Retrieved from: <https://www.easemble.com/features/augmented-reality>, 20.09.2025.
7. Hartmann, T., Fox, J. (2021). Entertainment in Virtual Reality and Beyond: The Influence of Embodiment, Co-Location, and Cognitive Distancing on Users' Entertainment Experience. In: P. Vorderer, C. Klimmt (Eds.), *The Oxford Handbook of Entertainment Theory* (pp. 717-732). Oxford: Oxford University Press.
8. *Industrial Augmented Reality*. Retrieved from: <https://www.ptc.com/en/technologies/augmented-reality>, 19.09.2025.
9. Ke, S., Xiang, F., Zhang, Z., Zuo, Y. (2019). A enhanced interaction framework based on VR, AR and MR in digital twin. *Procedia CIRP, Vol. 128*. pp. 753-758, doi: <https://doi.org/10.1016/j.procir.2019.04.103>
10. Koumporos, Y. (2024). Revealing the true potential and prospects of augmented reality in education. *Smart Learning Environments, Vol. 11*, pp. 1-62, doi: <https://doi.org/10.1186/s40561-023-00288-0>
11. Lang, B. (2021). *Locomotion Vault Catalogs & Compares 100+ VR Movement Techniques*. Retrieved from: https://www.roadtovr.com/locomotion-vault-vr-movement-techniques-catalog-database/#google_vignette, 18.09.2025.
12. Lee, K. (2012). Augmented Reality in Education and Training. *TechTrends, Vol. 56*, pp. 13-21, doi: 10.1007/s11528-012-0559-3
13. Li, G., Luo, H., Chen, D., Wang, P., Yin, X., Zhang, J. (2025). Augmented Reality in Higher Education: A Systematic Review and Meta-Analysis of the Literature from 2000 to 2023. *Educ. Sci., Vol. 15, Iss. 6*, doi: <https://doi.org/10.3390/educsci15060678>
14. LightGuide. *How AR-Powered Digital Work Instructions Drive Operational Excellence in Manufacturing*. Retrieved from: <https://www.lightguidesys.com/resource-center/blog/digital-work-instructions-explained-the-ultimate-guide/>, 20.09.2025.
15. Microsoft. *Usługa Dynamics 365 pomaga pracownikom współpracować i uczyć się*. Retrieved from: <https://www.microsoft.com/pl-pl/dynamics-365/topics/augmented-reality/what-is-augmented-reality>, 20.09.2025.
16. Pečečnik, K., Tomažič, S., Sodnik, J. (2023). Design of head-up display interfaces for automated vehicles. *International Journal of Human-Computer Studies, Vol. 177*, pp. 103060-103077, doi: <https://doi.org/10.1016/j.ijhcs.2023.103060>

17. PTC. *Vuforia: Market-Leading Enterprise AR*. Retrieved from: <https://www.ptc.com/en/products/vuforia>, 20.09.2025.
18. Rizov, T., Rizova, E. (2015). Augmented reality as a teaching tool in higher education. *International Journal of Cognitive Research in Science, Engineering and Education, Vol. 3*, pp. 7-15.
19. Robert, R., Breyer, F., Betts, J., Newnes, L., Shokrani, A. (2024). A Study of Commercial Augmented Reality Applications in Manufacturing: A Subject Matter Expert Analysis. *Procedia CIRP, Vol. 128*, pp. 186-191, doi: 10.1016/j.procir.2024.04.003
20. Sala, N. (2021). Virtual Reality, Augmented Reality, and Mixed Reality in Education: A Brief Overview. In: D. Choi, A. Dailey-Hebert, J.S. Estes (Eds.), *Current and Prospective Applications of Virtual Reality in Higher Education*. New York: IGI Global.
21. Sáez-López, J.M., Cózar-Gutiérrez, R., González-Calero, J., Carrasco, C. (2020). Augmented Reality in Higher Education: An Evaluation Program in Initial Teacher Training. *Educ. Sci., Vol. 10, Iss. 2*, doi: <https://doi.org/10.3390/educsci10020026>
22. Taqtile. *The AI-powered, everyday digital work assistant platform*. Retrieved from: <https://taqtile.com/manifest/>, 20.09.2025.
23. Tian, X., Ironsi, C. (2025). Examining the impact of augmented reality on students' learning outcomes. *Scientific Reports, Vol. 15*, doi: <https://doi.org/10.1038/s41598-025-20833-w>
24. Wang, X.M., Sothwick, D., Robinson, I., Nitsche, M., Resch, G., Mazalek, A., Welsh, T. (2024). Prolonged exposure to mixed reality alters task performance in the unmediated environment. *Scientific Reports, Vol. 14*, doi: <https://doi.org/10.1038/s41598-024-69116-w>
25. *What is a Head-up Display?* Retrieved from: <https://www.baesystems.com/en-us/definition/what-is-a-head-up-display>, 18.09.2025.
26. Zhao, X., Ren, Y., Cheah, K. (2023). Leading Virtual Reality (VR) and Augmented Reality (AR) in Education: Bibliometric and Content Analysis From the Web of Science (2018-2022). *SAGE Open, Vol. 13, Iss. 3*, doi: <https://doi.org/10.1177/21582440231190821>