STUDY OF THE COLLABORATIVE ROBOT OPERATION: DESIGN AND VALIDATION OF WORK PROCEDURES

AUGUSTIN STARECEK^1, NATALIA VRANAKOVA^1, BARBORA BOZALKOVA^1

^{1}Institute of Industrial Engineering and Management, Faculty of Materials Science and Technology in Trnava, Slovak University of Technology in Bratislava, Trnava, Slovakia

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augustin.starecek@stuba.sk

Collaborative robotics is a dynamically developing field that combines technical innovations with the principles of human-machine interaction. However, for the successful integration of collaborative robots, it is crucial to provide intuitive and user-friendly work instructions. The aim of the presented study was to design, create and validate standardized visualized work instructions for the basic operating functions of the collaborative robot MiR100 and UR5e. The methodological framework of the research combined bibliometric analysis and experimental testing of user workflows. The results confirmed the exponential growth of scientific interest in collaborative robotics and the contribution of visualized instructions to improving understanding, accuracy and subjective satisfaction of users. At the same time, visualized procedures reduced stress levels and supported independent interaction with the robotic system. The study emphasizes the importance of a user-centered approach and offers practical guidance for working more effectively with collaborative robots.

KEYWORDS

collaborative robotics, human–robot interaction, standardized work procedures, visualized workflows, user-centered design

1 INTRODUCTION

The rapid development of technology is changing the traditional work environment and creating new ways of cooperation between people and machines. Human-technology interaction is thus becoming a key factor in efficient and safe work procedures and instructions.

Collaborative robotics allows robots to work directly alongside people and support their activities, thereby increasing the productivity and flexibility of production and service processes. People organize their activities and work procedures, which affects their ability to effectively cooperate with technology. Therefore, it is essential that the design of collaborative robots takes into account not only technical accuracy, but also social and cognitive aspects of interaction.

Optimizing work procedures in an environment with collaborative robots requires, in addition to technical solutions, consideration of ergonomics, division of tasks and employee skills. The goal of HRI is to create a work environment in which technology complements human skills and supports harmonious and effective human-robot cooperation.

Human-Robot Interaction (HRI) is a dynamic field focused on enhancing communication and collaboration between humans and robots through various modalities, collaborative learning, and advanced technologies. At the core of Human-Technology Interaction (HTI) is the usability engineering paradigm, which seeks to enhance the effectiveness, efficiency, and satisfaction with which users can achieve their goals in a particular environment. Usability is often assessed through empirical methods such as user testing and heuristic evaluation. User Experience extends this by considering the user's emotions, beliefs, preferences, and perceptions during interaction with technology, which is crucial for designing systems that are not only functional but also pleasurable to use [Ntoa 2025, Sylvain 2024]. In the current era of rapid technological advancement, innovative solutions are constantly being introduced, highlighting the importance of their effective and optimal deployment [Gabajova 2021]. HRI utilizes various communication channels, such as visual, auditory, and tactile inputs, to enhance interaction between humans and robots [Safavi 2024]. Effective HRI is crucial for achieving shared goals in collaborative processes, with robots learning from human actions to improve their performance [Tashtoush 2021]. Studies have shown that human-robot collaboration can significantly enhance task efficiency and safety in various environments, including manufacturing and agriculture [Rodrigues 2023, Liao 2024].

Collaborative robots (cobots) are designed to work alongside humans, enhancing productivity and flexibility in manufacturing environments [de Nobile 2024, Rahman 2024]. Humans are inherently social beings who organize their actions and communication within social structures [Hrabcak 2017], a characteristic that strongly influences how they interact with collaborative robots. Research indicates that integrating social and cognitive dimensions into cobot design can enhance user acceptance and overall task performance [Crivelli 2025]. The development of methodologies for effective human-robot interaction is crucial, including the use of natural communication methods to improve task execution and collaboration efficiency [Neves 2024]. Managing cognitive workload is essential in human-robot collaboration to prevent overload and ensure that workers can maintain focus and efficiency [Carissoli 2024]. Design guidelines that consider cognitive ergonomics can help in creating systems that adapt to the psychological states of workers, thereby improving their interaction with cobots [Selby 2021].

Automation technologies, such as robotic process automation, can streamline processes, reduce human error, and enhance operational efficiency in various sectors [Shamsuzzoha 2025]. The increasing automation new competency requirements, emphasizing the need for continuous training to prevent skill degradation among employees [Rieth 2021]. Training programs that incorporate problem-based techniques and electronic work instructions can significantly enhance employees' problem-solving skills, leading to improved production efficiency [Anusin 2022]. The design of work instructions in technology-enhanced environments is informed by instructional design theories, which advocate for structured, learner-centered approaches to education and task execution [Mollard 2015, Cruz 2015]. Collaborative robots (cobots) are designed to work alongside humans, necessitating the development of safety guidelines to prevent injuries during interactions [Thierauf 2024]. Research indicates that optimizing the work pace and autonomy of human operators can significantly enhance job quality and reduce perceived workload [van Dijk 2023]. Effective communication between humans and robots is crucial for successful collaboration, with studies showing that human-like interactions can improve task performance and collaboration efficiency [Ferrari 2024].

2 MATERIALS AND METHODS

The methodological framework of the presented study within the framework of the implemented research is based on a combination of bibliometric analysis and experimental testing of user workflows. ***The main aim*** *of the study is the design, creation and validation of standardized visualized work instructions for the basic operating functions of the collaborative robot MiR100 UR5e.*

Two **research questions (RQ)** were defined within the framework of the research: (*1) How and in which scientific disciplines has interest in the field of collaborative robotics developed?* and *(2) What are the perceived benefits for users of standardized visualized workflows when working with the mobile collaborative robot MiR100 and UR5e?*

2.1 Description of the equipment used and the experimental environment

The MiR100 and UR5e devices, which are part of the equipment of the Institute of Industrial Engineering and Management at the Faculty of Materials Science and Technology of the Slovak University of Technology in Bratislava, were used for the purpose of carrying out the experiment. The mobile collaborative robot MiR100 (Mobile Industrial Robots) is an autonomous mobile platform (AMR) designed for the automation of internal logistics and material transport in industrial and logistics environments. The robot is characterized by its compact dimensions of 890 mm (length) × 580 mm (width) × 352 mm (height) and a total weight of 70 kg. The MiR100 is capable of transporting cargo with a maximum load capacity of 100 kg on a loading area of 600×800 mm. The robot is powered by a battery, while charging via a docking station takes approximately 3 hours (up to 80% in 2 hours). The device is combined with the UR5e collaborative robot, a six-axis robotic arm designed specifically for safe collaboration with humans in manufacturing environments. With a payload of 5.0 kg and a reach of 850 mm and excellent repeatability of 0.03 mm, it is suitable for precision tasks such as assembly, dispensing, material handling and other specialized applications, increasing flexibility and productivity. Fig. 1 shows the combination of the MiR100 and UR5e devices.

Figure 1. Combination of the collaborative robot UR5e and the mobile tugger MiR100 [own elaboration 2025]

For the purposes of creating workflows, the authors of the paper created visualizations of the laboratory in which the experiment was conducted. The first visualization was created in the MS VISIO software (Fig. 2).

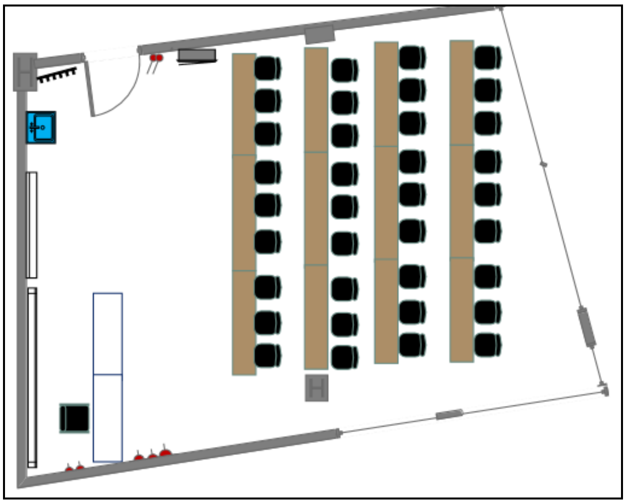


Figure 2. Laboratory visualization in MS VISIO [own elaboration 2025]

The advantage of the above visualization (Fig. 2) is the display of the real state, which can be used in the creation of workflows. The workflow will thus appear user-friendly. The visual was created after precise measurement of the laboratory. The disadvantage is the possibility of displaying it exclusively in 2D format. The next step was to implement the scanning output using the MiR100 device. At the same time, the above visualization demonstrates the real output of the tested scanning function. The real output can be seen in Fig. 3.

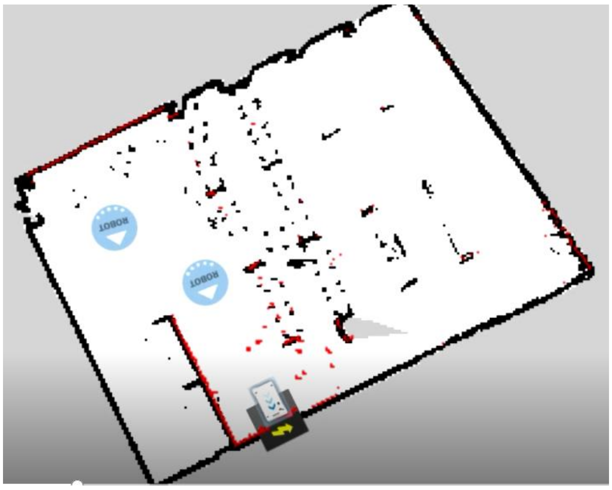


Figure 3. Scan and MiR environment [own elaboration 2025]

The main advantage of scanning (Fig. 3) is that the scanning device can make a quick and realistic visualization of the production space. The device displays static objects and load-bearing walls as black lines and shapes. At the same time, the device can also enter hard-to-reach spaces due to its size.

The experiment used represents a systematically designed empirical method that allows to verify the effectiveness of the proposed visualized workflows in a controlled, but also in a real environment. The advantage of the experiment is that it provides direct feedback on the user's interaction with the system — it allows to find out which steps are intuitive, which seem unclear and which lead to errors. In the field of human-robot interaction (HRI), experiments are essential for measuring user reactions, monitoring psychological and cognitive factors in real contexts and choosing between alternative solutions [Hoffman 2020]. Experimental verification is a key method for assessing user interaction with the system and identifying the strengths and weaknesses of the proposed workflows. It allows observing the real behaviour of participants when working with the device and revealing hidden problems that would not be possible to capture by theoretical analysis alone. The advantage of the experiment is the possibility of immediate observation, comparison of groups and interpretation of the practical impacts of the proposed solutions [Innes 2021]. The experiment involved 6 teachers and 6 students who had not received training in operating such a device and had no previous work experience with such or similar devices. All participants were divided into two groups: the Control Group and the Experimental Group. Each group consisted of three teachers and 3 students.

2.2 *Bibliometric analysis*

The first step in the bibliometric analysis was the selection of the world scientific databases Scopus and WoS. Subsequently, the frequency of scientific and professional publications from the given scientific databases was analysed according to the year of publication and affiliation to the scientific field. The next step in the bibliometric analysis was the processing of data from the Scopus database, which was selected to create the dataset. The starting file was 16,315 records obtained for the key term “Collaborative robotics”. In order to increase the relevance and quality of the analysis, we gradually applied the following filters: Document type: we selected only Articles and Conference Papers, which reduced the number of records to 14,405. Publication language: we applied the English filter, which reduced the file to 13,704 records. Access type: we kept only those records with the All Open Access status, which made the final analysable file 4,236 records. The data cleaned and filtered in this way were then exported in CSV format and used for the bibliometric analyses described below in the VOSviewer software.

To analyse research trends, thematic clusters, and interdisciplinary connections, we used VOSviewer software, which is a frequently used tool in the bibliometric community for visualizing bibliographic maps [Van Eck 2010]. VOSviewer enables the creation and visualization of maps based on various types of relationships among articles, authors, keywords, or institutions, such as co-authorship, keyword co-occurrence, citation, bibliographic coupling, and co-citation [Arruda 2022]. VOSviewer was chosen for the analysis because of its ability to visually represent and analyse complex relationships in scientific publications. It allows identifying research clusters, trends, and connections within a selected topic through multiple types of analysis. Its advantages are high clarity, ability to work with large datasets, and accessibility for the academic community.

3 RESULTS OF THE STUDY

The following part of the article is divided into two subchapters. The first contains an evaluation of the first research question, and the second part focuses on the evaluation of the second research question.

3.1 *Evaluation of the first research question*

Evaluation of **RQ1:** *How and in which scientific disciplines has interest in the field of collaborative robotics developed?* we can see in the text processed below. The first step of the analysis was the selection of two renowned world scientific databases, namely Scopus and Web of Science (WoS). In the above databases, we performed a conditional search for records based on the key term "Collaborative robotics". An important condition for the search was a filter limiting the results to publications published over the past 25 years (2001 to 2025). In total, 16,315 records were identified in the Scopus database and 16,690 records in the WoS database. Fig. 4 graphically shows the absolute frequency of occurrence of scientific articles focused on collaborative robotics in the monitored period in the Scopus and WoS databases. These analyzed data clearly demonstrate the exponential growth of scientific interest in the issue of Collaborative robotics.

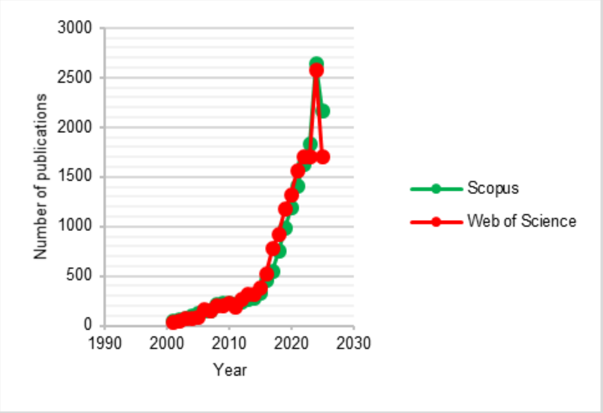


Figure 4. Trend in the number of publications in the Scopus and WoS databases in the field of collaborative robotics over the past 25 years [own elaboration 2025]

Fig. 4 graphically demonstrates the striking increase in interest in the topic of collaborative robotics in the field of research and scientific publications. In the initial phase, approximately from 2000 to 2012 until the official introduction of the new generation of cobots, the number of publications in both databases was low and relatively stable, with a maximum of 264 entries (manuscripts) per year. However, since 2015, there has been an exponential increase in publications, which corresponds to the more massive introduction of collaborative robotics into industrial practice and research. The publication curve rises steeply in 2023 and 2024, reaching maximum values ranging from 1708 to 2645 publications per year in both databases. Subsequently, the data for 2025 indicate a slight decrease, which is due to the fact that the analysis was carried out in September 2025 and there is still one quarter left until the end of the year. When comparing the databases, it is clear that although the overall growth trend is identical, the WoS database (red) consistently shows slightly higher absolute numbers of publications in the years of greatest interest compared to Scopus (green), which confirms the dynamism and expansion of published literature.

After identifying a total of 16690 relevant publications in the Web of Science Core Collection, the analysis was broken down into a more detailed structure focused on primary scientific areas. Fig. 5 visually demonstrates the distribution of these publications into WoS categories using a Tree Map, where the area size directly corresponds to the absolute frequency of records.

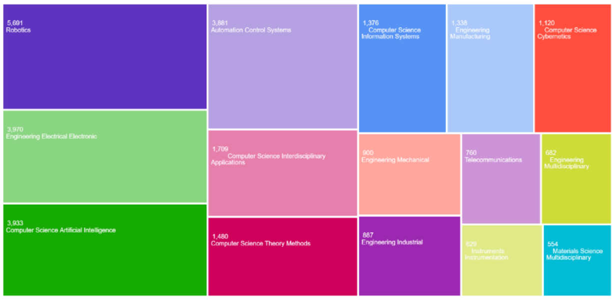


Figure 5. Tree Map was created in the Web of Science Core Collection for the topic of Collaborative robotics [own elaboration 2025]

Fig. 5 shows a Tree Map, which was created from the Web of Science Core Collection database, which visually represents the frequency of publications (16,690 records) by WoS categories.

The topic of collaborative robotics is strongly interdisciplinary, dominated by four main scientific fields. The largest and most important category is Robotics with a significant number of 5,691 publications. The second largest group is the Engineering Electrical Electronic area with 3,970 records, confirming the key role of sensors, actuators and electronic systems in ensuring safe collaborative operation. It is closely followed by Computer Science Artificial Intelligence with 3,933 records, indicating the growing importance of algorithms, machine learning and intelligent data processing for the autonomy and adaptability of cobots. The fourth dominant area is Automation Control Systems with 3,881 publications, underlining the technological importance of control and management in the context of collaborative robotics. Other significant categories with more than 1,000 entries include Computer Science Interdisciplinary Applications (1,709), Computer Science Information Systems (1,376), Engineering Manufacturing (1,338) and Computer Science Cybernetics (1,120). These categories, together with areas such as Engineering Mechanical (900) and Engineering Industrial (887), confirm that MiR100 and UR5e research and the creation of related workflows fall within the cross-section of the most relevant and dynamic scientific disciplines.

To obtain a more detailed overview of the research structure in the field of "collaborative robotics", which confirms the interdisciplinary nature of the topic, we used the WoS Research Assistant tool to generate a topic map, visually illustrated Fig. 6.

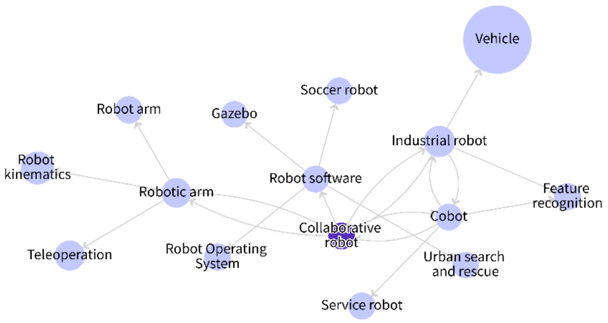


Figure 6. WoS keyword link map [own elaboration 2025]

The connectivity map shown in Fig. 6 identifies and visualizes the most important keywords and research directions, as well as their interconnections, and at the same time confirms that collaborative robotics is not an isolated field, but is closely connected to multiple subdisciplines. The hardware and application clusters include strong connections with nodes such as "robotic arm", "industrial robot" and "service robot". The largest node on the map, "Vehicle", points to the growing research in the field of mobile collaborative robotics and autonomous systems, which directly corresponds to the focus of our research on the MiR100 and UR5e mobile robots. The software and control clusters emphasize the key role of software through the nodes "robot software" and "robot operating system" (ROS), which are essential for programming and managing collaborative tasks. The kinetic and task clusters such as "robot kinematics" and "teleoperation" indicate the importance of precise motion control and remote control capabilities. The map also includes specialized applications such as "feature recognition", "urban search and rescue" and even "soccer robot". For our study, the most relevant connection between the central node "collaborative robot" and the node "vehicle" is the one that confirms the relevance of focusing on mobile collaborative platforms such as the MiR100 and UR5e and their key features that require standardized procedures for operation and deployment.

The final file from the Scopus database containing 4236 bibliographic records was subsequently exported in CSV format and used as the primary source file for detailed visualization and cluster analysis in the bibliographic software VOSviewer. The results of the country-level co-authorship analysis are visually illustrated in Fig. 7 co-authorship countries using overlay visualization.

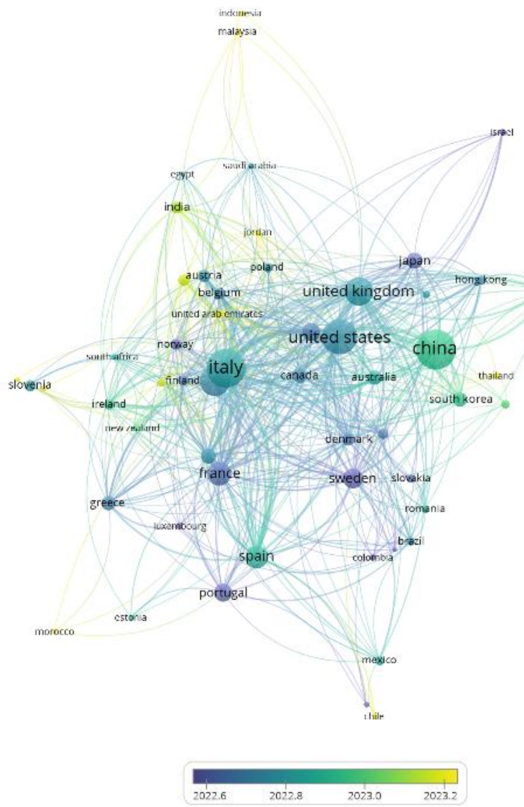


Figure 7. Co-authorship countries analysis from the Scopus database [own elaboration 2025]

The visualization (Fig. 7) shows that the size of the node corresponds to the number of publications, while the colour of the node and the link indicates the average year of publication (a shift from purple/blue to yellow-green indicates more recent research and more recent publications). It is clear from the map that the dominant position in research is maintained by the United States, China, Italy and the United Kingdom, which form the largest nodes and signal intensive international collaboration. The overlay visualization analysis further reveals that the most recent publications (yellow and light green shades – 2023.0 and later) come mainly from countries such as China, Singapore, South Korea and some Middle Eastern countries. This finding confirms that although traditional Western countries are still the strongest in terms of volume, Asia represents the most dynamically developing research center. European countries such as Italy, France and Germany form an interconnected cluster, while research in the V4 countries (including Slovakia) is closely integrated into this broader European context. The map clearly confirms the global relevance and timeliness of research in the field of mobile collaborative robotics.

To deepen the understanding of the current research agenda in the field of "Collaborative robotics", a co-occurrence map of indexed keywords was generated from the same set of 4,236 bibliographic records in the Scopus database, which is visually represented in Fig. 8. This map identifies and delineates seven main thematic clusters linked by the keywords "collaborative robots", "human-robot interaction" and "human". The cluster analysis reveals that research is primarily structured around these main lines: The red cluster focuses on industrial and safety integration, including keywords such as "Industry 4.0", "assembly line" and "human safety", which are critical for the implementation of MiR100. The green cluster is technically focused on control and autonomy algorithms and includes terms such as "robot programming", "multi-purpose robots", "path planning" and "slam", which are essential for mobile navigation. The yellow cluster is oriented towards learning and control with the keywords "machine learning" and "control". The blue cluster represents medical and surgical applications ("robotic assisted surgery"). Other clusters are devoted to mechanisms and control theory ("robot manipulators", "kinematics"), interaction and cognition ("user experience", "mental stress") and data and assessment ("risk assessment"). For our study, the connection between the central node and the clusters focused on industrial safety, programming and autonomy is key, confirming that the standardization of MiR100 operation is at the direct intersection of current scientific challenges in collaborative robotics.

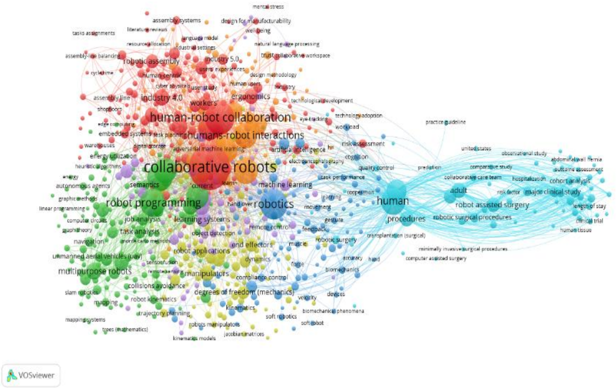


Figure 8. Co-occurrence – index keywords analysis from the Scopus database [own elaboration 2025]

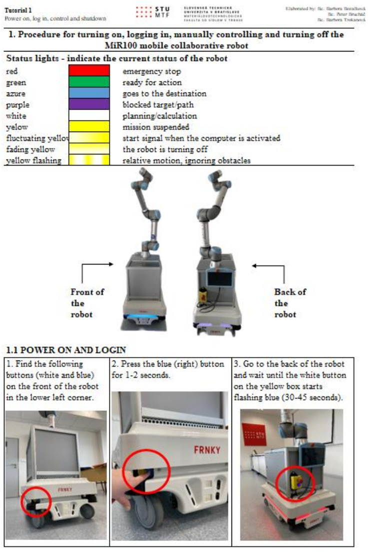
3.2 Evaluation of the second research question

Evaluation of **RQ 2**: *What are the perceived benefits for users of standardized visualized workflows when working with the mobile collaborative robot MiR100 and UR5e?* we can see in the text processed below.

For the purposes of the research, three workflows were designed and created, which used a combination of graphic visualizations, photos and texts to bring the hardware and software used closer to the user. The following three workflows were created as part of the experiment: A) The procedure for turning on, logging in, manually controlling and turning off the mobile collaborative robot MiR100, B) The procedure for charging the mobile collaborative robot MiR100 and C) The procedure for scanning a laboratory using the mobile collaborative robot MiR100. In Fig. 9 we can see an example of the workflow for task A and in Fig. 10 we can see an example of the workflow for task C.

Both workflows (Fig. 9 and Fig. 10) were used in the experiment to investigate the perceived benefits for users of standardized visualized workflows versus manufacturer-provided workflows.

For the needs of the study, a qualitative analysis was carried out in the form of an experiment. As part of testing the work procedures from the supplier, 3 teachers and 3 students were selected who had not completed training to work with the collaborative robot MiR100 and UR5e. For the needs of the study, three functions were selected that the participants of the experiment were to test, namely: A) turning on, turning off, logging in, controlling, B) scanning and C) charging. Time was not measured in the analysis so as not to create pressure on the subjects who were involved in the experiment. The analysis was carried out in the form of unstructured interviews that focused on the functionality and comprehensibility of the work instructions provided by the manufacturer and their perceived advantages and disadvantages.


Tutorial 1
Power on, log in, control and shutdown

STU MTF SLOVENSKÁ TECHNICKÁ UNIVERZITA V BRATISLAVE MATERIÁLOVOTECHNOLOGICKÁ FAKULTA SO SÍDLOM V TRNAVE

Elaborated by: Bc. Barbora Bezalková
Bc. Peter Bruchát
Bc. Barbora Trokanová

1. Procedure for turning on, logging in, manually controlling and turning off the MiR100 mobile collaborative robot

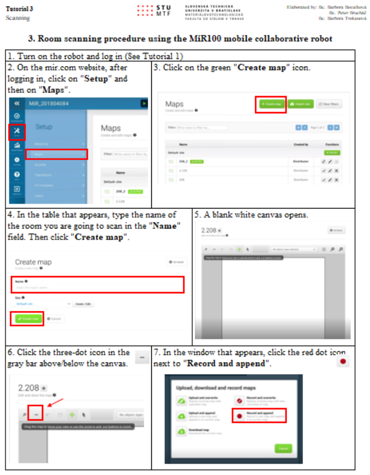
Status lights - indicate the current status of the robot

red	🟥	emergency stop
green	🟩	ready for action
azure	🟦	goes to the destination
purple	🟪	blocked target/path
white	⬜	planning/calculation
yelow	🟨	mission suspended
fluctuating yellow	🟨	start signal when the computer is activated
fading yellow	🟨	the robot is turning off
yellow flashing	🟨	relative motion, ignoring obstacles

1.1 POWER ON AND LOGIN

1. Find the following buttons (white and blue) on the front of the robot in the lower left corner.
2. Press the blue (right) button for 1-2 seconds.
3. Go to the back of the robot and wait until the white button on the yellow box starts flashing blue (30-45 seconds).

Figure 9. Laboratory scan workflow [own elaboration 2025]


Tutorial 3
Scanning

STU MTF SLOVENSKÁ TECHNICKÁ UNIVERZITA V BRATISLAVE MATERIÁLOVOTECHNOLOGICKÁ FAKULTA SO SÍDLOM V TRNAVE

Elaborated by: Bc. Barbora Bezalková
Bc. Peter Bruchát
Bc. Barbora Trokanová

3. Room scanning procedure using the MiR100 mobile collaborative robot

1. Turn on the robot and log in (See Tutorial 1)
2. On the mir.com website, after logging in, click on "**Setup**" and then on "**Maps**".
3. Click on the green "**Create map**" icon.
4. In the table that appears, type the name of the room you are going to scan in the "**Name**" field. Then click "**Create map**".
5. A blank white canvas opens.
6. Click the three-dot icon in the gray bar above/below the canvas.
7. In the window that appears, click the red dot icon next to "**Record and append**".

Figure 10. Workflow for basic functions on MiR100 and UR5e [own elaboration 2025]

The control group was always divided into three groups according to the function that the participants were to test. Each function was tested by one teacher and one student. In the control group, the test was successfully carried out for function A) switching on, switching off, logging in, controlling, even though the time exposure was relatively long. This was influenced by the fact that the teacher and student who tested the first function had no experience working with a similar device. Another factor was the workflow itself, which was not user-friendly. The same procedure was also chosen for function B) scanning and C) charging, where two other subgroups of participants were unable to perform scanning and charging without help. Only after the intervention of the experiment moderators were both functions put into operation.

Subsequently, another 6 participants were provided with a visualised workflow developed by us, which contained a precise and detailed procedure for working with the device for all three functions. A) switching on, switching off, logging in, controlling, B) scanning and C) charging. The experimental group consisted of 3 new teachers and 3 students, who again had no experience working with such or similar devices. An unstructured interview was conducted again after the work was completed, which focused on working with the device as well as the perceived user-friendliness of the workflow. Unlike the control group, all 6 subjects managed to perform the three tested functions. Within the first function switching on, switching off, logging in, controlling, the time was significantly shorter even without measurement.

From the results of the unstructured interviews, Table 1 was prepared, which contains a summary of the findings, which are categorized into advantages and disadvantages of the analysed work procedures.

Group	Results
Control Group	**Advantages**
	Text readability, comprehensiveness, and the ability to read more information about the device.
	Disadvantages
	Too long texts, images did not correspond to the real device (in form and quality of the photos), the workflow language was written for an active user with previous experience, too complicated, I was unable to complete the assigned task.
Experimental Group	**Advantages**
	Visualized workflow, detailed representation of all parts, optimal amount of text without unnecessary descriptions, the procedure corresponded to the real task, user-friendliness, it encouraged me to study further.
	Disadvantages
	Some images were less readable; the procedure was focused only on basic functions.

Table 1. Comparison of the results of guided interviews for the control and experimental groups [own elaboration 2025]

Based on Table 1, it is clear that visualized workflows, which were appropriately supplemented with high-quality images and an optimized amount of text, were perceived as more effective and beneficial compared to standard procedures. This conclusion supports the assumption that visual and personalized instructions have a higher user value when operating collaborative robotics. Based on unstructured interviews, it was demonstrated that both students and educators were encouraged to continue working with the device.

4 CONCLUSIONS

The research conducted in the presented study confirmed the growing global and interdisciplinary interest in the issue of collaborative robotics, with an exponential increase in scientific publications over the past decade, especially in the fields of robotics, automation and artificial intelligence. Experimental validation also demonstrated that visualized and standardized workflows significantly improved user understanding, accuracy of operations and positively perceived usability compared to the original manufacturer's instructions. Participants confirmed that visual workflows reduced uncertainty, stress and supported independent engagement in working with the robotic system.

From a theoretical perspective, the research contributes to the discourse on human-technology interaction by highlighting the importance of cognitive ergonomics and user-centered instructional design in the field of collaborative robotics. From a practical perspective, the validated procedures represent a model for the creation of standardized workflows that can improve the safety and efficiency of processes in industrial and educational practice.

The main limitation of the research is the relatively small experimental sample size and the qualitative nature of the feedback, which limits the statistical generalizability of the results. Future research should therefore expand the number of participants, include quantitative performance indicators (e.g., task completion time, error rate), and test the visualized procedures on other types of collaborative robots. It would also be appropriate to monitor the impact of standardized visual workflows on the level of user competence and process reliability over a long period of time.

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CONTACTS:

Augustin Starecek, Ing. PhD., Ing. Paed. IGIP
Natalia Vranakova, Ing. PhD.
Barbora Bozalkova, Ing.
Slovak University of Technology in Bratislava
Faculty of Materials Science and Technology in Trnava
Institute of Industrial Engineering and Management
Jana Bottu 2781/25, Trnava 917 24, Slovakia
augustin.starecek@stuba.sk
natalia.vranakova@stuba.sk
barbora.bozalkova@stuba.sk