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Teaching Cobots in Learning Factories – User and Usability-Driven Implications

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Abstract

Up to now, industrial robots were considered as machines working for humans. In this sense, programming required special coding knowledge and skills as teaching approaches were based on imperative programming methods, formulating the solving of a problem line by line. As novel work principles consider the robot rather a tool, assisting or collaborating with the human, declarative approaches are needed, that allow for intuitiveness and modifiability. Collaborative robot (cobot) control requires intuitive interfaces, not only for ease of use but also for modifying existing execution programs. Furthermore, the increasingly diverse personnel also requires a more democratic approach to robot programming. However, there is no standard or guideline for intuitive cobot control, and it can be noticed that the usability of the diverse interfaces and systems provided on the market is rather poor. This paper compares three systems with their advantages and disadvantages concerning usability and presents the results of the standard usability score (SUS) test, which was conducted in the Vienna learning factory "TU Wien Pilot Factory for Industry 4.0". Additionally, the paper presents an approach on how to teach different levels of cobot interaction and control addressing the skill sets needed in their individual working environments.

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Keywords: Learning Concept; Robot Programming; Cobot Teaching; Usability; Collaborative Robots

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1. Introduction

Collaborative robots (cobots) were developed to fill the gap between manual production and fully automated production as a result of varying market demands [1]. The use of industrial cobots in interactive human-machine tasks is considered a key driver towards smart factories, resp. Cyber-Physical Production Systems [2,3]. However, the industrial applicability shows that the ease of implementation is highly dependent on the required process and thus the integration of specific tasks and hardware as well as the level of operation [4,5]. Learning factories aim to provide a learning and teaching environment [6] coupled with a production situation in order to foster technological [7] or organizational [8] innovation or to develop competencies in dealing with new technologies [9]. An online search showed that during the last three years, cobots were featured in more than 10 % of the publications at the Conference on Learning Factories. This demonstrates the relevance of this topic. In Austria, cobots from different manufacturers were implemented in various scenarios in the learning factories in Vienna and Graz: In the smartfactory@tugraz e.g., cobots serve as flexible tools to be integrated in the assembly process of a shaft gearbox [10], while in Vienna, researchers evaluate different cobotic applications with regard to technical, economic and organizational effects [11]. Since different cobot manufacturers provide different user interfaces, which again imply advantages and disadvantages leading to a biased preference, the goal the authors are striving for is a user interface adaptable to varying user demands and thus providing different types of interaction and operation so as to being able to focus on the required competencies as a cobot user rather than the use of specific interfaces [12]. For instance, a layperson without a specific robotic knowledge in terms of technical basics such as kinematic dependencies should be able to interact safely with a cobot but does not necessarily need any programming or teaching interfaces. An operator on the shop floor should be able to make changes in the cobot control program, without necessarily making changes to the logical structure of the program or communication interfaces – in contrast to a cobot system integrator. With this adaptation of the user interfaces a democratization of cobot technology would become more accessible followed by a self-determination of work contents and work organization, allowing the use of a cobot as a tool e.g., supporting the user at the workplace. This versatility of applications and diversity of users requires an ease of use of the technology. Hence, this paper presents a teaching concept for cobots in learning factories based on the research results on usability of cobots.

2. Cobot User Interfaces and their Means of Interaction

In general, a UI is the point or way of a human interacting with a machine or an application. The UI determines how commands are given to the machine or application and how information is represented to the human. There are different modalities in which interfaces can be executed for cobots, such as visually by means of signal lamps, projectors or displays showing a representation of the cobot's mimic, acoustically by means of sounds or speech, haptically by means of keyboard and mouse, teach pendants, buttons, soft manipulators or smart surfaces such as sensory skins or safety mats. An overview of state-of-the-art modalities is also given in [13]. UIs for cobots not only address the interaction with the software, but also with the hardware and can be different depending on the purpose of the interaction. Implications on the UI design can be derived either based on the available UI on the market or based on the levels of interaction introduced by [14]:

- **Level 0 - Bystander** *(Basic interaction with cobot):* The bystander needs to know the system's state, i.e. whether the machine is in idle, automatic or error mode. This is often represented visually by signal lamps or by displays using either keywords or colors to identify the specific states. Furthermore, there is a need for buttons to either start, pause or stop the machine. Those buttons are again color-coded and identify their active status by blinking or static lights. The UIs applied are a way of interacting with the overall application.
- **Level 1 - Modifier** *(Basic modifications of cobot control programs):* Modifiers need to modify existing control programs of cobots by changing picking or placing positions due to manufacturing tolerances and variables such as dimensions or strokes of the end effector due to product changes, velocities or zoning parameters in order to optimize cycle time. Interfaces for this type of interaction can be represented either by displays, keyboards, mice,

etc. or by soft manipulators or voice control. The applied interfaces provide a way for interacting with modification parameters.

- **Level 2 - Programmer** *(Creation or modification of cobot control programs):* Programmers need to either create or modify control programs as the cobot has a new tool, needs to operate new or additional tasks or needs to add sensors to the application. Interfaces for this type of interaction are represented by means of intuitive programming methods such as teach-in, playback or block-based programming manifested in buttons, or interactive displays. The interfaces applied are a way of interacting with the manipulator.
- **Level 3 - Integrator** *(Integration of cobot work system into an existing environment):* The integrator needs to implement communication interfaces to peripheral equipment, such as tools, conveyors and sensors, as well as to upstream, downstream or higher-level machines or systems. Interfaces of this type of interaction are mostly represented by displays, keyboards or teaching pendants and are a way of interacting with peripheral equipment and other machines.

3. Cobot UI Evaluation in Terms of Usability

Weiss et al. [15] present a multi-level model for the evaluation of social robots, which includes usability, social acceptance, user experience and societal impact in addition to the main criteria of economic efficiency of an industrial cobot application. The focus of the presented work is on the evaluation of the cobots´ UI in a human-cobot interaction. As the tested cobot systems do not have any social cues (voice, eyes etc.), the work focuses on the factor usability, which is also part of the comparative analysis in [16]. The usability describes whether and how well or easy an object can be used and is an important factor for technical acceptance. The ISO 9241-11:2018 [17] describes usability as the "extent to which a system, product or service can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use". In order to check the usability of a product or device, various test procedures have been developed [18]. Brooke's method given in [19] has proven its worth in order to get a first all-embracing impression. As defined in the ISO standard, Brooke states, that "usability does not exist in any absolute sense; it can only be defined with reference to particular contexts." With the needs of the industry in mind, Brooke developed the system usability scale (SUS). The questionnaire consists of ten items, answered on a five point Likert scale. The result of this SUS questionnaire is a percentage value between 0 and 100, which is calculated by weighting the answers to the individual questions, i.e. 100 % corresponding to a perfect system without usability problems. Values above 80 % indicate good to excellent usability, values between 60 % and 80 % can be interpreted as borderline to good and values below 60 % are indications of considerable usability problems. With this, the usability of three cobots, which are located in the learning factory "Pilot Factory for Industry 4.0" at the TU Wien was examined. The study was conducted using a Universal Robot UR5, a Fanuc CR-7iA and a Franka Emika PANDA cobot. Fig. 1 shows the three programming interfaces of the cobots, which were evaluated in this study in addition to the given hand guiding/teaching possibilities.

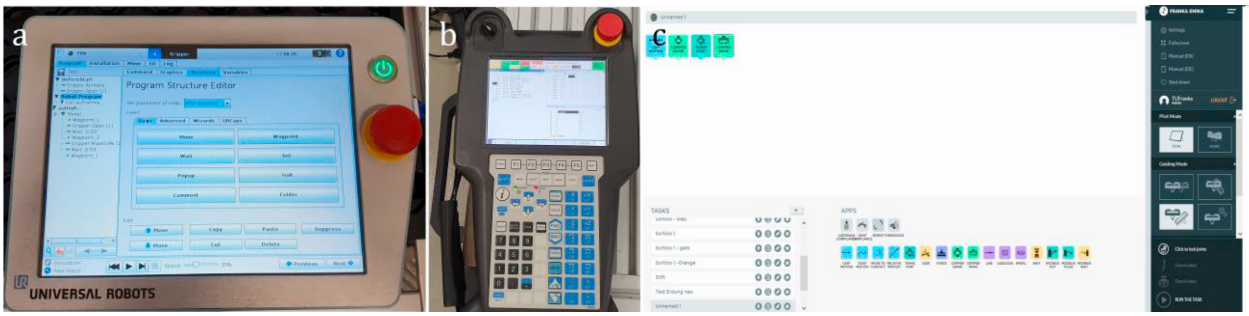

Fig. 1. Cobot UIs: (a) Universal Robot UR5; (b) Fanuc CR-7iA; (c) Franka Emika PANDA.

Within the framework of a voluntary participation in a training for cobot use, mainly students from different disciplines were asked to fill out a questionnaire on the usability of one of the cobot systems. The experiment took place on different days and on different cobots, but always in the learning factory and with the same procedure. After a safety briefing and a short introduction to the topic of cobots, the participants were asked for their expectations in the form of a short questionnaire. Then they had to complete a task independently with the cobot including programming and/or teaching the cobot. During the interaction, the participants had the possibility to ask other participants or the instructors for help. Afterwards the participants were asked to fill out the usability questionnaire. The questionnaire used was the SUS from [19] complemented with some additional questions in the end, concluding with the question, if they would like to reengage with the cobot in the future.

In total, the study is comprised of 36 participants (21 male / 15 female) with a mean age of 28.53 years (SD = 5.35). Almost 53.8 % of the participants already had previous interactions with another cobot or robot (control) system. The distribution of the participants regarding the tested cobots was not equal, with 36.1 % evaluating the UR, 33.3 % the Fanuc and 31.6 % the Franka Emika. The average SUS over all cobots was 59.0 %, which indicates considerable usability problems. Looking at the average SUS, the best overall system was the Franka Emika with 70.6 %, followed by the UR with 55.4 % and the Fanuc with 52.3 %, whereas, the sequence changes to Fanuc and UR, if ranked by median. The distribution over all cobots and participants is shown in Fig. 2. There was a significant positive correlation between the SUS and the question how comfortable (coef. = 0.73, $p < 0.05$) and how safe (coef. = 0.39, $p < 0.05$) the participants felt during the interaction. Participants with a prior experience with a robot (control) system rated the usability significantly worse than participants without (coef. = -0.41, $p < 0.05$). There was no significant correlation between the SUS and the previous expectation about ease of use (coef. = -0.21, $p = 0.23$). After the interaction, in total two participants did not want to interact anymore with the cobot in the future (one with Franka Emika and one with Fanuc). In summary, all cobots considered have achieved a poor usability value. The results also undercut those in [16], where UR was rated with 62.4 % and Franka Emika with 85.4 %. After the questionnaire, the participants also had the chance to add some additional comments about their interaction experience. In the course of which eight participants criticized the UI itself (three after interacting with UR, four with Fanuc and one with Franka Emika) and four about the heavy or non-ergonomic teaching pendant (two after interacting with UR and Fanuc respectively).

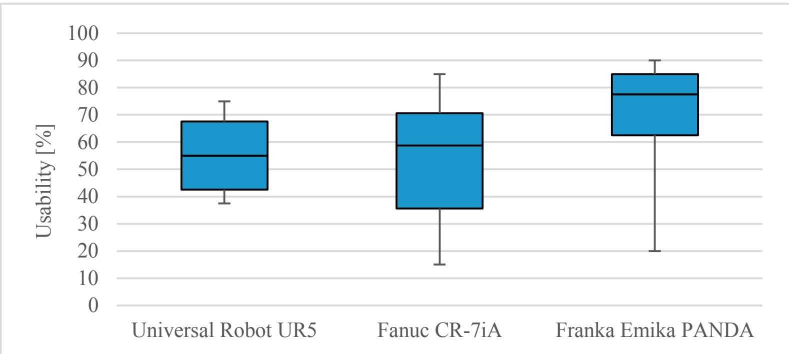

Fig. 2. Comparison of participant individual SUS results including the medians.

4. Learning Concept for Cobot Teaching

Initially, it was proposed to democratize cobot technology as a tool. Based on the poor results of today´s cobot systems, which shows that there is yet work to be done in order to create intuitive cobot UI, there is a need for a learning concept for cobot teaching. There are different education or teaching concepts including traditional frontal lecture, blended learning, action-oriented, group-based teaching and project or case study based teaching [20], without claiming to be exhaustive. Given the framework of the above answered questions, a combination of the concepts is needed to fulfill the objective. First, the learning objectives based on the learning target dimensions (LTDs) as in [9] were defined and hence a teaching concept was derived (see Table 1). This adaptable teaching concept on individual levels based on the user needs was developed and tested on students and laypersons more than ten times in the learning factory and at other institutions at the TU Wien (e.g., Living Lab in Library, Knowledge Hub) as well as externally e.g., in a makerspace for level 0 and 1 within the last year. Furthermore, the concept was applied in the learning factory as well as directly at manufacturing companies in more than five industrial requests (once level 0, once level 1, twice level 2, once level 3) and one training course within the framework of adult education (deploying level 0-2).

Table 1. Teaching concept based on levels of interactions and required competencies derived from LTDs.

Level of Interaction	Required Competencies	Cognitive LTD	Affective LTD	Psycho-motoric LTD	Teaching Concept
Level 0 - Bystander	Safety understanding.	Safety related interaction modalities; Possible risks.	Awareness of possible risks.		Combine the generally appropriate safety instructions with the cobot-specific instructions to create an easy-to-understand document. A handout leaflet and a safety warning near the cobot are strongly recommended. Make sure that everyone has understood the safety instruction – test the learners.
Level 1 - Modifier	Influences of modifications; Kinematic structure of the cobot and its motion behavior.	Possible modifications in software; Basics of mechanics/ kinematics.	Acceptance of technical restrictions. Trust in reliability.	Natural guiding by hand/ teaching with ease.	Provide very basic theoretical knowledge about physical properties of the cobot (e.g., kinematics). Show technical properties, possibilities and restrictions (e.g., kinematics, reachability) directly on the cobot. Enable a first physical interaction with the cobot. Give learners a possible goal, which should be achieved with the help of the cobot.
Level 2 - Programmer	Logical understanding; Basic programming knowledge.	Programming interface; Dependencies[1] basics.	Awareness of dependencies.		Explain the first programming interface of the cobot (e.g., workflow or task based). Provide a documentation of the procedure (e.g., interactive and workflow-based) for programming the cobot. Give learners a challenging goal, which should be achieved with the help of the cobot.
Level 3 - Integrator	Advanced technical knowledge; Interface design; Advanced programming knowledge.	Dependencies[1] advanced; Safety; Security.	Acceptance of safety and security requirements.		Explain the system architecture of the cobot (hardware and software) theoretically in the form of graphics, text documents and directly using the cobot. Provide documentation about the safety certification requirements [21,22]. Develop and provide a guide for consistent user interface design.

5. Conclusion and Future Work

It has been shown that the usability of today's cobots indicates considerable challenges and that there is a need for a teaching concept to fit the needs of different cobot user groups. In this sense, learning targets for humans have been identified and a learning concept to achieve these targets was proposed. In the future, this concept will be elaborated based on meaningful sets of competencies organized in the form of small entities, so called “Learning Nuggets”. These “Learning Nuggets” can be consumed in a short period of time, typically between 5 to max. 30 min. The overall goal is the set-up of an educational platform that allows the democratization of cobot technology for different levels of interaction for various user levels. Therefore, a comprehensive competence matrix to define the required competences to be able to work out the targets and learning concepts in detail is developed. Furthermore, the improvement of cobot

[1] of sensors, actuators, power supply, processors etc.

technology towards inherently safe and self-explicable use still offers extensive opportunities for advancement [23]. However, not only research institutions and the learning factory community are challenged, but first of all cobot developers and manufacturers. As e.g., the teaching pendant or tablet was not welcomed by the participants, it is recommended to cobot producers to develop and provide intuitive UIs, which are located either on a screen (e.g., the Franka Emika system) or combine several modalities like hand-guiding and teach-by-voice or a completely context-driven, thus process-integrated form of programming without any recognizable UI. From a learning factory's perspective, it can be stated, that quality UI design increases the acceptance of a cobot as an assistance system in manufacturing and serves as a facilitator for the training of assembly operations – even for non-experts, laypersons and people that are usually not interested in industrial processes. Following this empirical evidence, cobots can be considered as learning tools in order to enhance creativity and public acceptance of manufacturing and industry. This approach might lead to a further level ("Level X") for user and usability-driven learning concepts in learning factories [24].

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References

[1] L. Wang, R. Gao, J. Váncza, J. Krüger, X.V. Wang, S. Makris, G. Chryssolouris, Symbiotic human-robot collaborative assembly, CIRP Annals – Manufacturing Technology, 68 (2019) 701-726.
[2] S. Schlund, F. Baaij, Describing the technological scope of industry 4.0-a review of survey publications, LogForum, 14-3 (2018).
[3] O. Salunkhe, M. Gopalakrishnan, A. Skoogh, A. Fasth-Berglund, Cyber-Physical Production Testbed: Literature Review and Concept Development, Procedia Manufacturing, 25 (2018) 2-9.
[4] W. Mayrhofer, D. Kames, S. Schlund, Made in Austria – Produktionsarbeit in Österreich 2019, https://owncloud.tuwien.ac.at/index.php/s/kZ7sFwhraxORhWw, (accessed Jan. 2020).
[5] A.P. Calitz, P. Poisat, M. Cullen, The Future African Workplace: The Use of Collaborative Robots in Manufacturing, SA Journal of Human Resource Management, 15-1 (2017) 1-11.
[6] A. Djuric, V.M. Jovanovic, D. Foster, Hands-On Learning Environment and Educational Curriculum on Collaborative Robotics, ASEE Annual Conference Proceedings, (2017) 1-15.
[7] J. Wermann, A.W. Colombo, A. Pechmann, M. Zarte, Using an Interdisciplinary Demonstration Platform for Teaching Industry 4.0, Procedia Manufacturing, 31 (2019) 302-308.
[8] S. Mattson, O. Salunkhe, A. Fast-Berglund, D. Li, A. Skoogh, Design Concept towards a human-centered Learning Factory, Procedia Manufacturing, 25 (2018) 526-534.
[9] E. Abele, J. Metternich, M. Tisch, G. Chryssolouris, W. Sihn, H. ElMaraghy, V. Hummel, F. Ranz, Learning factories for research, education, and training. Procedia CIRP, 32 (2015) 1-6.
[10] hi!tech, Agile Fertigung für die smarte Produktion, https://www.hitech.at/industrie/agile-fertigung-fuer-die-smarte-produktion/, (accessed Jan. 2020).
[11] hi!tech, Teamwork 4.0: Mensch und Roboter, https://www.hitech.at/industrie/mensch-roboter-kollaboration/, (accessed Jan. 2020).
[12] J. Kildal, A. Tellaeche, I. Fernández, I. Maurtua, Potential Users' Key Concerns and Expectations for the Adoption of Cobots, Procedia CIRP, 72 (2018) 21-26.
[13] S. El Zaatari, M. Marei, W.D. Li, Z. Usman, Cobot programming for collaborative industrial tasks: An overview, Robotics and Autonomous Systems, 116 (2019) 162-180.
[14] T.B. Ionescu, S. Schlund, A Participatory Programming Model for Democratizing Cobot Technology in Public and Industrial Fablabs, Procedia CIRP, 81 (2019) 93-98.
[15] A. Weiss, R. Bernhaupt, M. Lankes, M. Tscheligi, The USUS Evaluation Framework for Human-Robot Interaction, AISB2009: Proceedings of the Symposium on New Frontiers in Human-Robot Interaction, 4-1 (2009) 11-26.
[16] F. Ferraguti, A. Pertosa, C. Secchi, C. Fantuzzi, M. Bonfè, A Methodology for Comparative Analysis of Collaborative Robots for Industry 4.0, Design, Automation and Test in Europe, (2019) 1070-1075.
[17] ISO 9241-11:2018: Ergonomics of human-system interaction – Part 11: Usability: Definitions and concepts.
[18] N.A. Stanton, P.M. Salmon, L.A. Rafferty, G.H. Walker, C. Baber, D.P. Jenkins, Human factors methods: a practical guide for engineering and design, (2017) CRC Press.

[19] J. Brooke: SUS – A quick and dirty usability scale, P. W. Jordan, B. Thomas, B. A. Weerdmeester, and A. L. McClelland, editors, Usability Evaluation in Industry, (1996) Taylor and Francis.
[20] M. Götting, F. Gosewehr, M. Müller, J. Wermann, M. Zarte, A.W. Colombo, A. Pechmann, E. Wings, Methodology and Case Study for Investigating Curricula of Study Programs in Regard to Teaching Industry 4.0, 15th International Conference on Industrial Informatics, (2017) 533-538.
[21] ISO 10218-2:2011: Robots and Robotic Devices – Safety Requirements for Industrial Robots – Part 2: Robot Systems and Integration.
[22] ISO/TS 15066: 2016: Robots and Robotic Devices – Collaborative Robots, International Organization for Standardization.
[23] T.B. Ionescu, S. Schlund, C. Schmidbauer, Epistemic Debt: A Concept and Measure of Technical Ignorance in Smart Manufacturing, 10th International Conference on Applied Human Factors and Ergonomics, (2019) 81-93.
[24] F. Ansari, P. Hold, W. Mayrhofer, S. Schlund, W. Sihn, Autodidact: Introducing the Concept of Mutual Learning into a Smart Factory Industry 4.0, 15th International Conference on Cognition and Exploratory Learning in Digital Age, (2018).