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Guidelines for the integration of cognitive ergonomics in the design of human-centered and collaborative robotics applications

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Abstract

In the context of Industry 4.0, cognitive ergonomics is crucial for improving the working conditions and the psychosocial well-being of operators interacting with even more advanced and smart machines, as well as for the enhancement of production performances. Nevertheless, this topic is often neglected or ignored when implementing human-robot interaction in industrial settings. Starting from the results obtained from previous studies, this work proposes a structured process to develop and preliminarily validate a set of guidelines to support non-experts in human factors at the early stages of the design of human-centered and collaborative applications. A systematic analysis of the scientific literature has been performed by an interdisciplinary team of researchers to identify relevant results on the topic. Successively, the guidelines have been developed starting from such an analysis by considering the target group and the final aim of the work. This phase involved the analysis, classification, summary, and abstraction of relevant statements and results from the selected articles, as well as the update of the previous set of guidelines. The guidelines have been preliminarily validated by an external team of researchers currently doing research in the field. Qualitative feedback on understandability and relevance has been collected to improve the guidelines before further investigations.

Keywords: human-robot interaction ; collaborative robotics ; cognitive ergonomics ; Industry 4.0 ; human-centered design.

1. Introduction and motivation

Collaborative robotics is one of the main and enabling technologies of Industry 4.0. When designing collaborative systems, cognitive ergonomics and human factors are often overlooked [1]. This is a serious shortcoming, especially when humans have to continuously and strictly share workspaces and tasks with advanced and intelligent automation [2]. It is widely demonstrated that human factors deeply affect operators' safety, well-being, and work-related performance [3]. Consequently, designers have to consider cognitive ergonomics to develop human-centered and efficient collaborative systems [4]. In the future, more and more workers will collaborate with industrial robots to perform their job. On the one hand, robots will help humans perform stressful and demanding activities, acting as physical or cognitive assistance systems. On the other hand, iHRI represents an emerging risk in sociotechnical systems. In particular, it implies profound technical and

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organizational changes in production systems design and management [5] by potentially introducing ergonomics-related issues such as increasing cognitive load [6], stress and burnout [7], information overload [8], loss of motivation and frustration [9], and reduced safety [10]. Cognitively straining conditions lead to occupational hazards for workers' health, safety, and well-being, negatively affecting work performance and productivity [11]. These unfavorable conditions are strictly related to the use of emerging technologies, the organization of work activities, and the way by which operators can interact with production systems (e.g. human-machine interfaces). In that regard, considering the field of iHRI, human trust towards robots [12], robot acceptance [13], and human-robot teaming [14] are relevant topics that have been preliminarily studied in the field of social and industrial robotics. In a previous work [15], the authors underlined the necessity to support technicians in easily and intuitively considering cognitive requirements while developing advanced collaborative applications. Technical standards and deliverables [16] are commonly used in industrial engineering to support companies in the accomplishment of design requirements. These usually include principles (e.g. guidelines) on how to create state-of-the-art products, systems, and services. Nowadays, except for some parts of ISO TR 9241-810 [17], standards for the design of human-centered and cognitive-oriented production systems based on iHRI are missing. Thus, considering the relevance of the topic and starting from previous results of the authors (see [1],[18],[19] and Fig.1 for further details), this work proposes a structured process to develop and preliminarily validate a set of guidelines to support non-experts in human factors (e.g. industrial engineers, roboticists and system integrators) in designing anthropocentric and (human-robot) collaborative production systems.

Fig. 1. First test experimental set-up [19].

2. Methodology

The proposed guidelines have been developed by an interdisciplinary team of researchers (industrial engineers and occupational psychologists) with previous experience on the topic. The proposed approach is inspired by the methodology provided by the National Institute for Health and Care Excellence (NICE) [20]. The main phases for the guidelines' development, revision, update, and preliminary validation are summarized in Fig. 2 and described hereafter.

Systematic analysis of the scientific literature

A systematic analysis of the scientific literature was initially performed to identify relevant results and new evidence on human factors and cognitive ergonomics in iHRI. In particular, 615 papers published between 2020 and 2022 have been analyzed by using Scopus as the main database. The following search criteria have been used: TITLE-ABS-KEY((ergonomics OR ergonomic OR "human factors" OR "human-factors" OR "cognitive" OR "cognitive ergonomics" OR "psychology") AND ("Collaborative Robotics" OR "Human Robot" OR "Collaborative Robot" OR "Human Robot" OR "CoBots" OR "Human - Robot" OR "HRI" OR "HRC")) AND (LIMIT-TO (PUBYEAR,2022) OR LIMIT-TO (PUBYEAR,2021) OR LIMIT-TO (PUBYEAR,2020)). Considering the aim of this work, articles addressing the following topics have been discarded: (i) study on healthcare robotics, (ii) study on social robotics (e.g. humanoids, robots designed for interaction with children, elderly people, people with disabilities, etc.), (iii) teleoperated robots, (iv) virtual robots, (v) exoskeleton, (vi) studies on human-robot task allocation. After an internal evaluation, articles referring to the above topics were considered only if related studies were evaluated as of very high or generalized relevance. Articles remaining after the filtering process are listed in the reference list (from [21] to [78]).

Guidelines development and integration

Starting from the results of the analysis of the scientific literature, the guidelines have been developed by considering the target group and the final aim of the work. The methodology is following summarized: Step 1 – Analyze, extract, and divide relevant and validated statements and results from the selected articles; Step 2 - Summarize the identified contents by reducing them to single sentences; Step 3 - Merge similar concepts among the same article (note that one article's results can provide more guidelines); Step 4 - Merge redundant or similar guidelines among all the analyzed articles; Step 5 - Update the previous set of guidelines (see [19]) by considering the new ones; Step 6 - Simplify and abstract the overall guidelines as much as possible without losing the core principles; Step 7 - Homogenize the lexicon and classify the guidelines according to similar contents by using different categories.

Guidelines preliminary revision and intermediate update

The guidelines created in the previous phase have been preliminarily analyzed by an external team of researchers working on the topic at the Department of Industrial and Manufacturing Engineering of the University of Malta (https://www.um.edu.mt/eng/ime). Qualitative feedback on understandability and relevance has been collected to improve the first version of the guidelines before further investigations.

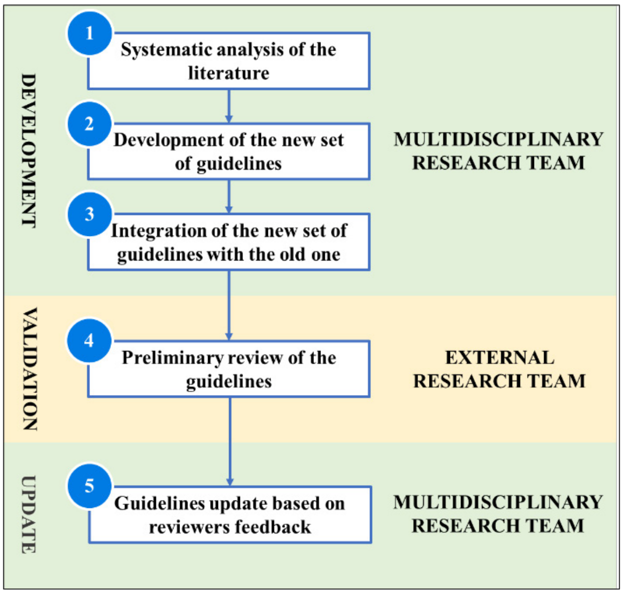

Fig. 2. Process for guidelines development, revision, and update.

3. Results

In the following, the list of reviewed guidelines is presented.

Guidelines category: Workstation and Robot System Features

1. Locate the robot system as distant as possible from the user's position according to the required level of interaction
2. Design the visual appearance of the workstation using low-contrast workstation elements with respect to the robotic system
3. Design workstation elements aligning user inputs with corresponding system outputs in a manner that reflects natural human behavior (e.g., a left button press on an alarm on the left side of the screen)
4. Provide functions of the workstation systems (including the robotic system) that adapt to the user's preferred working methods
5. Realize a fluent and smooth aesthetic robotic system design (i.e., avoid bulky joints, wires, external arm components, mechanized shape)
6. Design robotic the system and related devices with industrial appearance (i.e., avoid adding social appearance and human-like features, e.g., anthropomorphism)
7. Avoid similar type, color, and appearance of multiple robotic systems that have to interact with the user (entitative groups of similar robots can be seen as threatening)

Guidelines category: Robot System Performance and Interaction Patterns

8. Provide measures for the adaptation of robotic system behavior and interaction patterns to correspond with a user considering the capabilities and skills of the user
9. Make the robotic system able to understand, interpret and anticipate the user's actions, intentions and decisions like in human-human interactions (i.e. goal-oriented)
10. Allow the robotic system to adapt its behavior and communication mode considering previous interactions and works made in collaboration with the user (i.e., adaptability by learning)
11. Design comprehensible, consistent, and legible robotic system behavior (e.g., avoid supposedly arbitrary actions of the system)
12. Avoid (frequent) variations in robot system velocity (by considering a slow velocity as a reference starting value)
13. Avoid similar behavior of multiple robotic systems that have to interact with the user during the same tasks
14. Implement object's transfer in the natural reach zone of the user during physical interactions
15. Make the robotic system able to anticipate the user's intents to (physically) interact before the interaction occurs and ignore user's false positive actions if relevant for the interaction
16. Coordinate the actions of both the user and robotic system to avoid conflicts (e.g., collisions)
17. Adopt various user-centric approaches for the design of pleasurable interaction patterns and interfaces (e.g., usability methods based on focus groups, thinking aloud, questionnaires, and expert evaluation)
18. Implement social conventions to prevent the communication of an erroneous intent by the robotic system (e.g., handing over a screwdriver by offering its handle)

Guidelines category: Human-Robot Communication and Interfaces

19. Support users and robotic systems to share the same communication model (e.g., language) and use vocabulary that is simple and easy to understand
20. Suggest work breaks to improve user's performance and concentration
21. Make the robotic system send requests of interaction in such a way to least interfere with the user's motor activity, attention and context comprehension
22. Make the user intuitively and immediately aware of the robotic system status, behavior and intentions when relevant and necessary
23. Customize information amount, form, content, and communication mode considering user's individual interaction strategy
24. Allow the user to provide feedback to the robotic system to confirm or reject a proposed action plan if needed
25. Provide measures that allow the robotic system to explain its decisions to the user when necessary and applicable
26. Inform the user about the type and functioning of specific safety measures used during the interaction
27. Design interfaces in such a way that the signalling modality, form and timing support to the user can lead him/her easily and unambiguously understanding information
28. Make the robotic system able to deliver apology statements (in case of errors or mistakes) and competence statements when useful or necessary
29. Simplify robot-to-human communication by avoiding unnecessary information overload (i.e. prioritize and combine information gathered from multiple channels using the minimum number of feedback interfaces)
30. Avoid the risk of misinterpretation of received or visualized information by the user (i.e., prevent potentially contradictory, conflicted or delayed information exchange)

31. Provide multimodal and complementary communication channels in a redundant way
32. Provide measures to communicate with the user without losing the focus on the task (e.g., transfer the graphic user interface onto the collaborative workspace or design on-board devices for visual communication)
33. Allow the user to understand a forthcoming task in advance (e.g. by using preparatory notifications)
34. Allow the user to intuitively understand beforehand the intentions of the robotic system, the spatial occupancy of its planned motions and signal its target and interested workpieces

Guidelines category: Control measures

35. Simplify the direct control of the user on the robotic system (i.e., commands must be explicit and intuitive)
36. Provide workstation systems (including the robotic system) that adapt safety strategy to the user's preferences
37. Provide robot system features that help the user without removing her/his expertise
38. Allow the user to provide real-time corrections to key arbitrary robotic system's state and in case of disagreement with its autonomous behavior
39. Allow the user to set the preferred level of autonomy of the robotic system (by considering a medium-level as reference starting value)

Guidelines category: Organizational Measures and Training

40. Demonstrate to the user the effectiveness and reliability of safety measures of the robotic system prior to start the interaction
41. Demonstrate to the user the efficiency and reliability of the robotic system elements (e.g., the capability of the end-effector to firmly hold a workpiece during the whole task) prior to start the interaction
42. Make the robotic system perceived by the user as a useful, effective and reliable companion (and not only as a tool) instead of a competitive entity
43. Use common language and human-like terminology when presenting the robotic system to the users and terminology that highlights its cooperativeness
44. Engage operators in workstation, interface, interaction, job sequence design and evaluation following an iterative process and including a multidisciplinary design team
45. Provide training and empowerment to the user when designing, implementing and working in the workstation (e.g., understand the abilities, the process complexity, the limitations of the robotic teammate and the reasons behind the events)
46. Provide measures to support the user in experiencing meaning, feeling responsible for outcomes, and understanding the results of her/his efforts
47. Promote a "process champion" who agreed on the technology and can cascade this knowledge to the rest of the team
48. Enable user's positive initial experiences with the robotic system during the early interaction period to prevent disuses or misuses
49. Support users without prior experiences to judge and compare the capabilities of the robotic system with their own
50. Support the management (prior to the development of the workstation) to clearly communicate its intent, rationale, goals, effects, commitment and support to the changes related to the new technology introduction
51. Consult users and stakeholders during the hazard identification, risk assessment and safety measures validation
52. Prevent user's limited agency, perceived control and responsibility over the work that the delegation of decisions and tasks to the robotic system may introduce
53. Implement measures to counteract deskilling of operators when possible and appropriate

4. Conclusions and future works

This work presented a structured process to develop a set of guidelines to support non-experts in human factors in designing anthropocentric and collaborative applications. Soon, the guidelines will be reviewed and updated according to the outcomes of a survey that has been developed by the authors to deeply and widely investigate how experts in different disciplines (i.e., industrial engineering, robotics, safety of machinery, human factors, and ergonomics) can interpret and judge the guidelines. Participants will be asked to evaluate the guideline's understandability and usefulness and to suggest practical solutions for their implementation in industrial contexts, as well as an assessment method and key performance indicators to evaluate their effectiveness. Results will be organized in such a way as to contribute to the development of a "toolkit" that aims at properly supporting designers and system integrators without previous experience in human factors in providing practical solutions to crucial cognitive requirements in advanced iHRI

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