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User-centered design in mobile human-robot cooperation: consideration of usability and situation awareness in GUI design for mobile robots at assembly workplaces

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Abstract: Mobile cobots can increase the potential for assembly work in industry. For human-friendly automation of cooperative assembly work, user-centered interfaces are necessary. The design process regarding user interfaces for mobile human-robot cooperation (HRC) shows large research gaps. In this article an exemplary approach is shown to design a graphical user interface (GUI) for mobile HRC at assembly workplaces. The design is based on a wireframe developed to support situation awareness. An interactive mockup is designed and evaluated. This is done in two iterations. In the first iteration, a user analysis is carried out using a quantitative survey with $n = 31$ participants to identify preferred input modalities and a qualitative survey with $n = 11$ participants that addresses touch interfaces. The interactive mockup is developed by implementing design recommendations of the usability standards ISO 9241 – 110, 112 and 13. A heuristic evaluation is conducted with $n = 5$ usability experts and the measurement of situation awareness with $n = 30$ end users. In the second iteration, findings from the preceding iteration are implemented in the GUI and a usability test with $n = 20$ end users is conducted. The process demonstrates a combination of methods that leads to high usability and situation awareness in mobile HRC.

Keywords: user-centered design; graphical user interface; situation awareness; usability engineering; human-robot cooperation

1 Introduction

1.1 Background

In production and construction, there is currently a high shortage of skilled workers and an ever-increasing complexity [1, 2]. The Corona pandemic has increased personnel shortages [3]. This leads to the fact that the use of robots working together with humans, the so-called human-robot cooperation (HRC), is gaining importance [4, 5]. Especially easy-to-use interfaces become more and more important, because they increase the acceptance of automated systems by the users [6, 7]. In the context of the investigation on the future use of mobile, ad-hoc cooperating robot teams for industrial applications [8, 9], this research adapts existing methods for user-centered development for the design of a graphical user interface (GUI) for mobile HRC. Here, a user interface is designed for the HRC to support humans in the work task at assembly workplaces. Figure 1 shows the demonstrator of the project in field tests. The demonstrator was programmed as an example to take servo motors from a shelf and insert them into a container table in sequence. This corresponds to one of the steps performed today by assembly personnel. In parallel, the worker carries out assembly steps, e.g. greasing the motor shafts and screwing in the inserted servo motors. During the human-robot cooperation, the worker always has the robot's activity and its current status in view with the help of a GUI, as well as the overall goal of the assembly task. A dynamic system is present because both the cobot and the worker are continuously moving around while performing the common work task. At the same time, the work object is constantly changing its shape due to the assembly process. Since this is a dynamic system, the construct situation awareness is highly relevant [10]. This was already included in the design of the wireframe, the pre-model of the GUI. When operating

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Figure 1: Demonstrator for mobile HRC in a field study.

the GUI during assembly, usability is also of high relevance. Both aspects are considered and evaluated in this work. The ways to choose and combine methods for a GUI for mobile HRC are diverse and context dependent.

1.2 Related work

Previous work on the topic of mobile HRC is mainly technology-oriented [11–13]. Approaches that pursue user-centered design draw on ISO 9241-110. For example, a service robot was developed for customers in a hardware store. An evaluation by end users took place in a field test. The implementation of the principles is not described [14, 15]. Related to human-robot cooperation, research is also being conducted on a control loop model for human-centered design. The context is general, it does not talk about a mobile robot in an assembly context [16]. For a robotic arm attached to a wheelchair, GUIs were designed and tested using a System Usability Scale [17]. For a mobile robot for elderly care that is remotely controlled by a caregiver, a user interface was developed where both situation awareness and usability were evaluated. The workload was assessed by means of a questionnaire and NASA-TLX was used as an assessment tool. Usability was determined by using a System Usability Scale questionnaire and situation awareness was measured by applying the 3D-SART method [18]. A guide to support the design of usable user interfaces for human-robot collaboration at the production workplace was developed, where the process phases were divided into analysis, iterative design, and evaluation [19]. The user-centered design of a GUI for human-robot collaboration was also investigated for mechanical joining processes in aircraft final assembly [20]. An iterative user-centered design process in human-robot interaction was also applied in a robot for agricultural vineyard spraying [21], where a heuristic evaluation was performed. The iterative design of a mobile assistance system for maintenance workers applies design guidelines and standards for software ergonomics [22]. However, the user-centered approaches do not address the same factors that are addressed in this research, such as the industry context, mobile HRC, or GUIs. Be it the lack of user-centered design intent or the industry context, especially the reference to cooperation at assembly workplaces.

The user-centered design process according to ISO 9241-210 recommends the application of design principles, among others from ISO 9241-110, 112 and 13, when designing user interfaces. Inspection methods are particularly economical for evaluation because they can be carried out in a short time [23], such as the heuristic evaluation according to Nielsen [24]. An evaluation of elaborated user interfaces should also be performed with end users. These usability tests can be conducted with standardized questionnaires such as IsoMetrics or ISONORM 9241/110, both of which are similarly meaningful [25]. An overview of usability methods has been implemented in a taxonomy. It is divided into the classes Testing, Inspection, Inquiry, Analytical Modeling and Simulation [26, 27]. In order to measure situation awareness in a user interface, the application of different methods is possible. The situation awareness measurement methods ASAGAT, CARS, PASA, QUASAGAT, SAGAT and SPASA were compared [28, 29]. Similarly, a direct comparison of both SAGAT and SART methods has been conducted [30, 31]. These are mostly questionnaire-based and differ, among other things, in that the questions are asked either during the execution of the experiment – by briefly pausing the experiment – or afterwards. From 4-point to 7-point Likert scales are recommended to evaluate performance and situation awareness. The previous process which is the starting point for this research consisted of the phases Goal-Directed Task Analysis, Physical Model, and wireframe design, in which design principles for situation awareness were implemented. One view on the GUI represents the overall goal, one represents the status of the robot related to its current activity, and one shows the checklist to verify that the current task is being performed correctly (see Figure 2). The existing wireframe has been pre-evaluated using qualitative interviews. The measurement of situation awareness can only be done once an interactive mockup has been created. As further preliminary work, a GUI was developed to enable intuitive programming [32]. This should

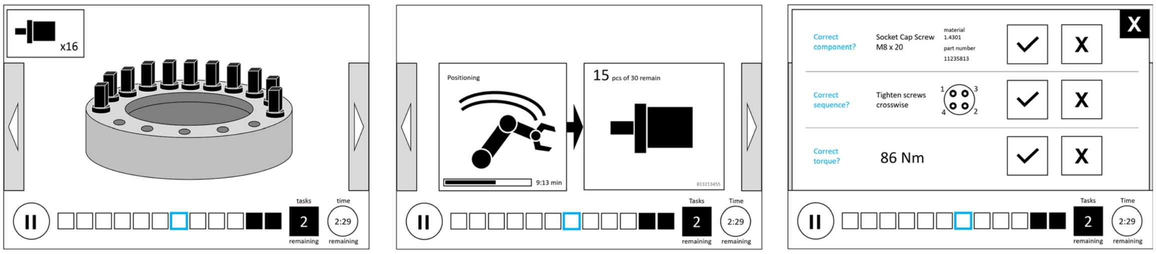


Figure 2: Wireframe design as source material for performing usability engineering; overall goal view (left), robot view (middle), checklist view (right).

also be implemented in the GUI for HRC in order to be able to evaluate the user-centered approach here as well.

1.3 Motivation and research question

The motivation of this work is to develop an approach to design a user interface to support usability and situation awareness in a mobile HRC. It has been shown that there is a current need for user-centered user interfaces for mobile HRC. Preliminary work has already been done by developing a wireframe that defined relevant information that targets human-robot cooperation for situation awareness [33]. Similarly, a GUI for intuitive robot programming has been developed that can take a holistic approach through its implementation in the HRC [32]. The next step completed through this work is to create an interactive mockup to evaluate the GUI in terms of usability and to measure situation awareness. The value of this research for science is to show a process how to design a GUI for mobile HRC that supports situation awareness and usability. The following research question arises:

Which combination of methods can be used to design a GUI that supports situation awareness and usability for mobile HRC at assembly workplaces?

2 Methods

2.1 Experimental task

In the use case, a mobile robot is used in an industrial environment to assist in assembly by having workers and robot work on a common work task. As in the previous work to develop a wireframe [33], the work task consists of assembling a container table for a labeling machine in the beverage industry. For this study, the complex assembly task was reduced from 25 to 4 steps. These are the greasing of motor shafts (step 1), the insertion of servo motors into a container table (step 2), the greasing of screws (step 3) and the screwing of the servo motors to the container table (step 4). Human-robot cooperation is realized insofar as worker and robot share the workspace while working on the common work task. The worker can also assist the robot in positioning the servomotors or screws the already placed drives in the meantime. Figure 3 shows the elements and resources for the work task and the task allocation. The sequence as it is handled during the execution of the task in this use case is shown in a slide diagram, based on the Gantt diagram of an assembly sequence for human-robot cooperation [34].

The work task of container table assembly is a suitable application for mobile HRC because it was assessed in the work system analysis as monotonous, which could result in errors for workers [35]. Related to the theory of assembly in industrial production, the use case corresponds to a stationary, manual assembly of large equipment [36]. This creates a dynamic system that makes mobile HRC useful and supportive. The individual assembly steps can be assigned capabilities that are proven in assembly theory [37]. Greasing components corresponds to the capability “lubrication”, inserting servo motors corresponds to “handling” and screwing servo motors corresponds to the capability “pressing on/in”, which is described in the German standard DIN 8593-3.

2.2 Experimental design: user-centered design process

A user-centered design process has been applied, as described in ISO 9241-210. The context of use described in this document has already been carried out in previous work [33, 35]. In this research, the approach is carried out in two iterations. The first iteration includes a user analysis, the design of the interactive mockup, the heuristic evaluation and the measurement of the situation awareness. The second iteration includes the design of the GUI by implementing the findings from the previous evaluation and a usability test with end users by applying the questionnaire ISONORM 9241/110. Figure 4 shows an overview of the applied process. The description is divided into “Process Phase”, “Chapter”, Method and “Goal of the Method”. Each of the methods relates to the research objective as follows: The quantitative survey examines which input modalities are preferred by the target group when operating GUIs, because the input form has a strong influence on the GUI design. The qualitative interview picks up on the preferred input modality and ask users about their experiences, because the use of familiar elements leads to higher user acceptance. An interactive mockup is necessary to measure situation awareness and test usability. The heuristic evaluation results in suggestions for improvement of the GUI with the help of experts. The situation awareness evaluation makes measurement of situation awareness possible and additionally obtains feedback from users. The high fidelity mockup synthesizes all the findings into a holistic GUI design so that this can then be tested with potential users in a usability test. The HRC specification of the process

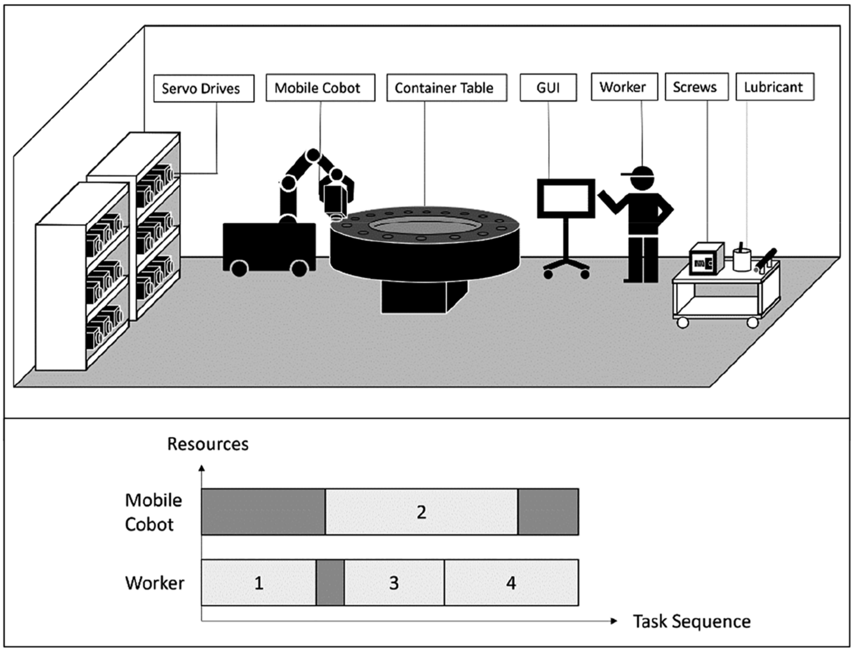
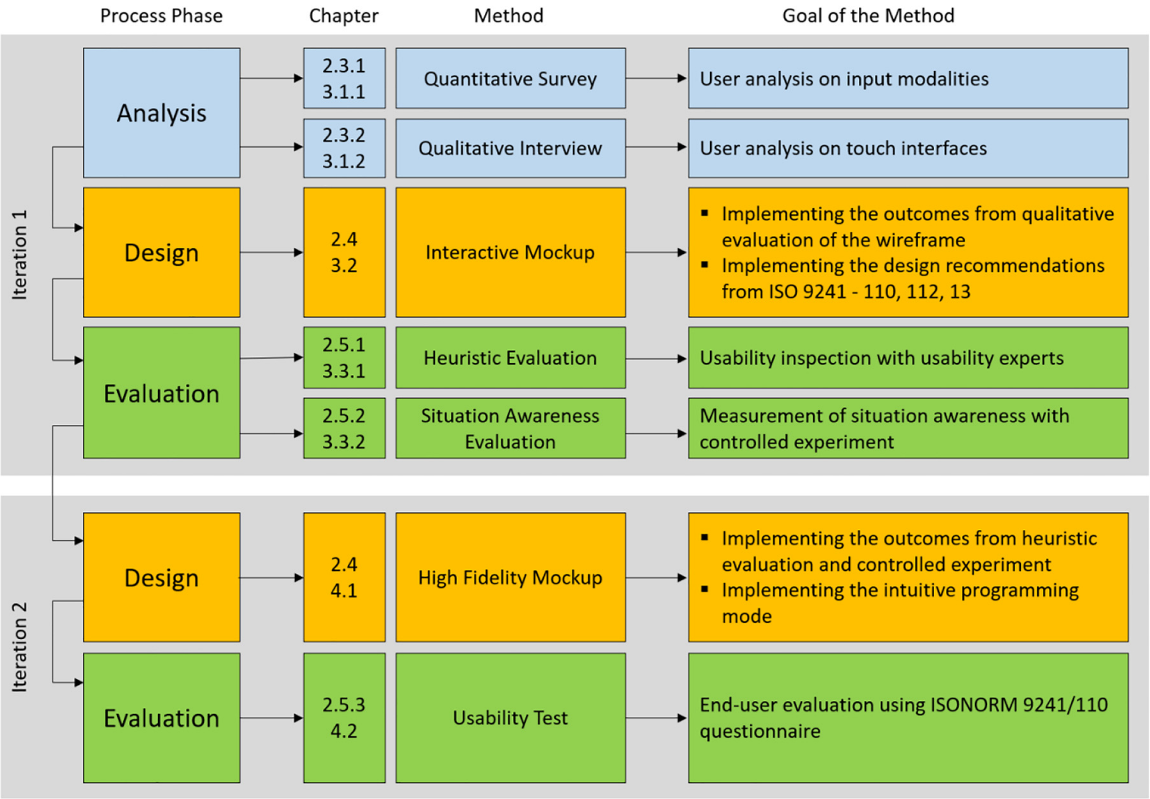


Figure 3: Elements and resources for work task and task allocation.



	Process Phase	Chapter	Method	Goal of the Method
Iteration 1	Analysis	2.3.1 3.1.1	Quantitative Survey	User analysis on input modalities
		2.3.2 3.1.2	Qualitative Interview	User analysis on touch interfaces
	Design	2.4 3.2	Interactive Mockup	▪ Implementing the outcomes from qualitative evaluation of the wireframe ▪ Implementing the design recommendations from ISO 9241 - 110, 112, 13
	Evaluation	2.5.1 3.3.1	Heuristic Evaluation	Usability inspection with usability experts
		2.5.2 3.3.2	Situation Awareness Evaluation	Measurement of situation awareness with controlled experiment
Iteration 2	Design	2.4 4.1	High Fidelity Mockup	▪ Implementing the outcomes from heuristic evaluation and controlled experiment ▪ Implementing the intuitive programming mode
	Evaluation	2.5.3 4.2	Usability Test	End-user evaluation using ISONORM 9241/110 questionnaire

Figure 4: Approach to a method combination for the user-centered design process of a GUI for mobile HRC.

mainly results from the relevance of the constructs situation awareness and usability because the context refers to mobile HRC, not stationary HRC.

2.3 User analysis methods

2.3.1 Quantitative survey on input modalities: The user analysis consists of two studies to obtain information about potential end users on the use of user interfaces and modalities. The first analysis is a survey on the experience with different input modalities and the preference of certain ones for the user interface of the cobot. Figure 5 shows the input modalities that are available for selection in the survey. The two questions asked are "How often do you use this input modality in everyday life?" and "Can you imagine this form of input in human-robot collaboration?" The questions were each rated by the respondents using a 4-point Likert scale. For the evaluation a score is assigned to each item. In reference to the question "How often do you use this input modality in everyday life?" the items "Almost daily" (score 3), "Weekly" (score 2), "Rarely" (score 1) and "Never" (score 0) are available for selection. Related to the question "Can you imagine this form of input in human-robot collaboration?" the items "Very well" (score 3), "Basically" (score 2), "Less" (score 1) and "Not at all" (score 0) are available for the participants to choose from. For both questions, scoring is conducted in the same manner. For each input modality, the scores are summed, and then the mean and standard deviation are calculated.

There were 31 respondents, of which 27 were male and 4 were female, ranging in age from 17 to 60 years ($M = 37.19$; SD = 13.35) and work experience in manufacturing from 2 to 42 years ($M = 17.53$; SD = 12.22). All respondents work in the assembly department and thus correspond to potential end users of the robotic system.

2.3.2 Qualitative interview on touch interfaces: The second analysis consists of qualitative interviews with assembly workers. The topic of the questions is derived from the preferences for input modalities. Since touch systems performed best in the previous survey, they will be addressed in the qualitative interviews. The people are asked which touch systems they use in everyday life. They are also asked how they cope with the touch systems and individual apps on smartphones. The interviews were audio recorded and transcribed. Subsequently, a qualitative content analysis according to Mayring was conducted to evaluate the interviews [38]. The transcripts were paraphrased and coded. A coding agenda was created and the frequency of mentions of elements (e.g., apps used) was shown. The coding agenda contains numbered categories, the definition of a category, and an anchor example in which the interview number and the page number of the text passage are written. Furthermore, the coding rules are written when a text passage is assigned to a category and according to which criteria it is assigned. 11 workers participated in the survey. All were male, from 26 to 50 years old ($M = 40.1$; SD = 8.63).

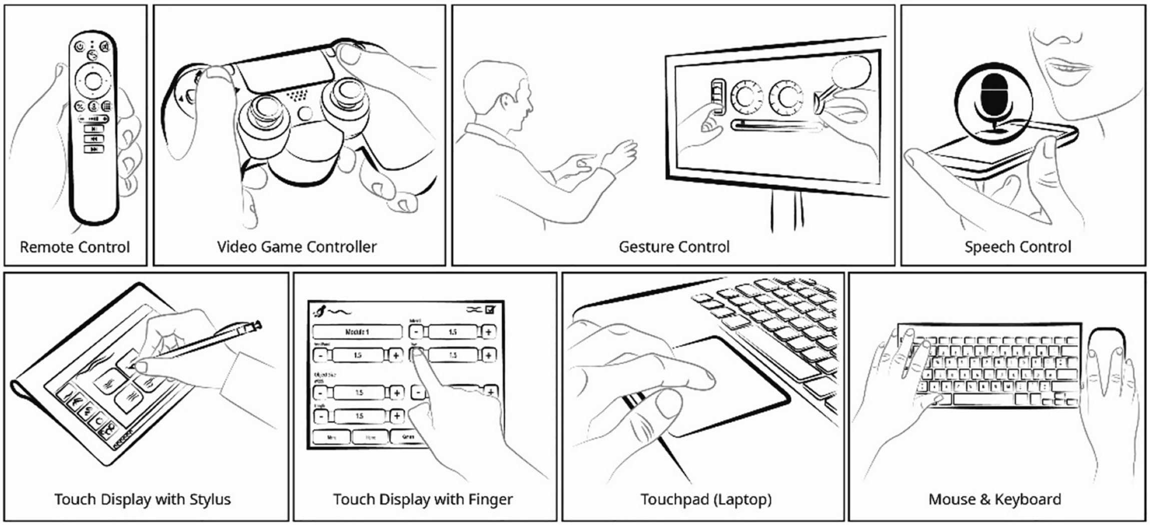


Figure 5: Input modalities that are available for selection in the quantitative survey.

2.4 Design methods

In the first iteration, the design of the interactive mockup is done by applying design principles from parts 110, 112 and 13 of ISO 9241 and by implementing the outcomes from the wireframe evaluation in the previous research. ISO 9241-110 recommends the 7 design principles of *suitability for the task, self-descriptiveness, conformity with user expectations, suitability for learning, controllability, error tolerance and suitability for individualization*. These principles are based on the 2016 version, and although the 2019 version includes a slightly modified form of the principles, the 2006 version is compliant with the ISONORM 9241/110 questionnaire. The ISO 9241-112 standard contains principles for presenting information in order to design systems that are suitable for use, whether visual, auditory or tactile. These are the 6 principles of *detectability, freedom from distraction, discriminability, unambiguous interpretability, conciseness and consistency (internal and external)*. The ISO 9241-13 standard deals with user guidance for human-system interaction, which is divided into the following topics: *common guidance recommendations, prompts, feedback, status information, error management, and on-line help*. In the second iteration the design is done by implementing the outcomes from the heuristic evaluation and the controlled experiment. Also the intuitive programming mode from the previous work is implemented, so that it results in a high fidelity mockup.

2.5 Evaluation methods

In the first iteration, the evaluation consists of a heuristic evaluation and a measurement of situation awareness. In the second iteration it consists of a usability test by means of ISONORM 9241/110 questionnaire.

2.5.1 Heuristic evaluation: The heuristic evaluation according to Nielsen was conducted with $n = 5$ usability experts working in the mechanical engineering industry. They all design and develop user interfaces for industrial applications in their daily work. The reviews with the experts take place as individual interviews. In heuristic evaluation, each individual reviewer examines the user interface alone to ensure an independent and uninfluenced review. The reviewers evaluate the user interface with respect to Nielsen's 10 heuristics and enter the current status and suggestions for improvement for each principle.

2.5.2 Situation awareness evaluation with controlled experiment: The first draft of the GUI, which was designed and evaluated as a wireframe, is designed to support situation awareness. By means of an interactive mockup, situation awareness can be measured. Here, a measurement was performed that is adapted from SAGAT [39]. The evaluation setup consists of a test room in which participant, moderator, and facilitator are located. The test person views two screens during the measurement. The work task is simulated by showing the situations of the individual work steps on one screen. On a second screen the current GUI is shown. Figure 6 shows the evaluation setup of the controlled experiment.

The participant has to perform four work steps and has to name the interaction performed at the interface. Performance and situation awareness are measured by 20 questions. The questions related to situation awareness are divided into task awareness (TA) and robot awareness (RA). They are questions related to level 1, 2 and 3 for situation awareness. The performance is evaluated by the researchers. Performance was assessed by the researchers by checking "yes" on the sheet if the question was answered successfully and "no" if the question was not answered successfully. After each question, the tester is asked how useful the information on the GUI is. The respondent has to indicate this on a 6-point Likert scale, from "very helpful" to "not helpful at all". This corresponds to scores from 100 (very helpful) in increments of 20 down to 0 (not helpful at all) for situation awareness. For each question, the scores are multiplied by the number of people who selected that item. Then the results for each question are added up and divided by the maximum possible score (high score = 3000). This yields the situation awareness scores for each question. The values are divided into the topics TA, RA and total values. Mean values and standard deviations are calculated for each topic. Figure 7 illustrates the calculation of the situation awareness as an example.

The study involved 30 people, all of whom worked as assemblers in the production department of a company that manufactures machinery and equipment for the beverage industry. They are therefore end users of the interface developed. Thirty people were interviewed, 27 of whom were male and 3 female, ranging in age from 17 to 60 years ($M = 37.6$; SD = 13.38) and work experience in manufacturing from 2 to 42 years ($M = 17.78$; SD = 12.35).

2.5.3 Usability test with end users: In order to evaluate the usability of the GUI, a usability test is conducted using the standardized questionnaire ISONORM 9241/110. For the evaluation setup the laboratory environment was chosen, which displays both the working environment and the GUI on two screens, analogous to the situation awareness measurement. The evaluation involved 20 assembly workers who are potential end users for the developed interface. 17 participants were male and 3 female, ranging in age from 17 to 54 years ($M = 34.75$; SD = 12.30) and a work experience in manufacturing from 1 to 38 years ($M = 16.15$; SD = 10.16). The usability test includes 19 tasks for operating the user interface during a hypothetical performance of the assembly task.

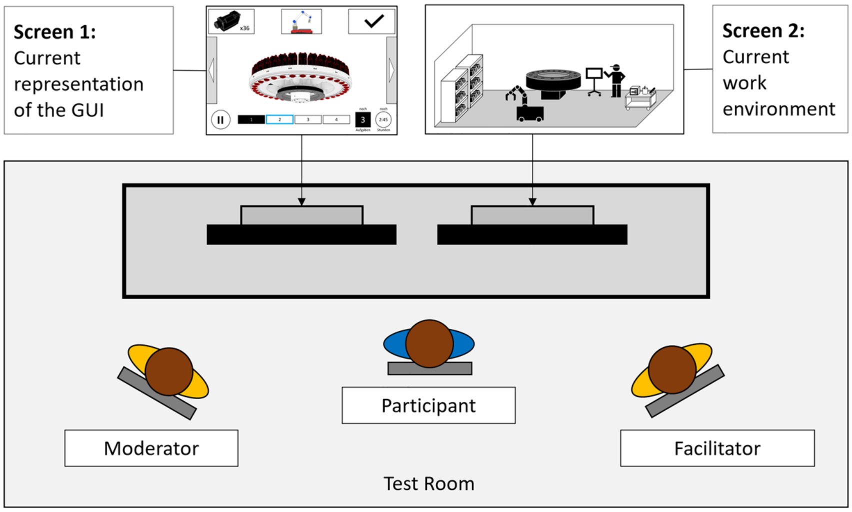


Figure 6: Evaluation setup of the controlled experiment.

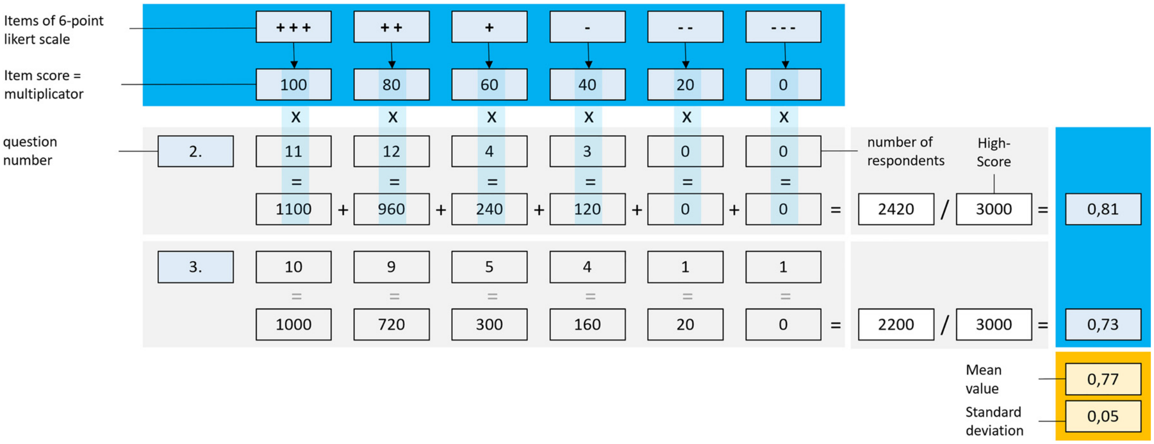


Figure 7: Calculation of situation awareness as an example.

After completing the tasks, each respondent completed the ISONORM 9241/110 questionnaire. The performance of the persons during the tasks as well as the ratings in the questionnaire were evaluated.

3 Results of first iteration

In the previous chapter, the methods of development were explained in more detail. In this chapter, the results of the user-centered design process are described. The results of the analysis are divided into quantitative and qualitative surveys. The results of the design are divided into the applied parts of ISO 9241 and the visualization of the results. Afterwards, the result of the evaluation is explained and the results are illustrated in a visualization of the graphical user interface in order to recognize connections between GUIs and principles from ISO 9241. The results of the evaluation are divided into the heuristic evaluation and the situation awareness measurement.

3.1 User analysis

To carry out a user analysis, the quantitative survey was conducted to investigate the workers' experience with input modalities and to identify which modalities are preferred for the use case. A qualitative survey was conducted to analyze the basic experience with touch systems.

3.1.1 Result of quantitative surveys on input modalities

The survey on input modalities for GUIs has produced quite clear results. In terms of the use of input modalities, the 3 most common are mouse & keyboard, touch display with finger and the remote control. Gesture control is the least used. When asked how suitable an input form is for use for human-robot interaction at the assembly workplace, opinions lean strongly toward touch display with finger and touch display with stylus. Input via gesture control is the least imaginable. A correlation between the frequency of use of certain input forms and how suitable these input forms are for HRC in the assembly task is not discernible, or the factors are only weakly related to each other. Figure 8 shows the results of the survey on input modalities.

3.1.2 Result of qualitative interviews on touch interfaces

The findings of the surveys on touch interfaces revealed that the respondents use a manageable number of touch interfaces in their everyday lives. The first thing they came across were smartphones or tablets; they first had to be introduced to other devices with touch displays, e.g. navigation devices in cars, ATMs or ordering displays in fast food restaurants. When asked about apps used on smartphones, the number of apps is equally manageable. Every person surveyed who owns a smartphone also uses the messenger app *WhatsApp*. Frequently used apps are the social network *facebook*, the map service *Google Maps* and the video portal *YouTube*. When asked about the satisfaction of touch systems used, the participants surveyed are generally satisfied with the apps they use. Likewise with displays for ordering food at *McDonald's*. They are more dissatisfied with the user guidance of navigation devices. Table 1 shows the coding agenda for the qualitative survey, divided in category, definition and anchor example.

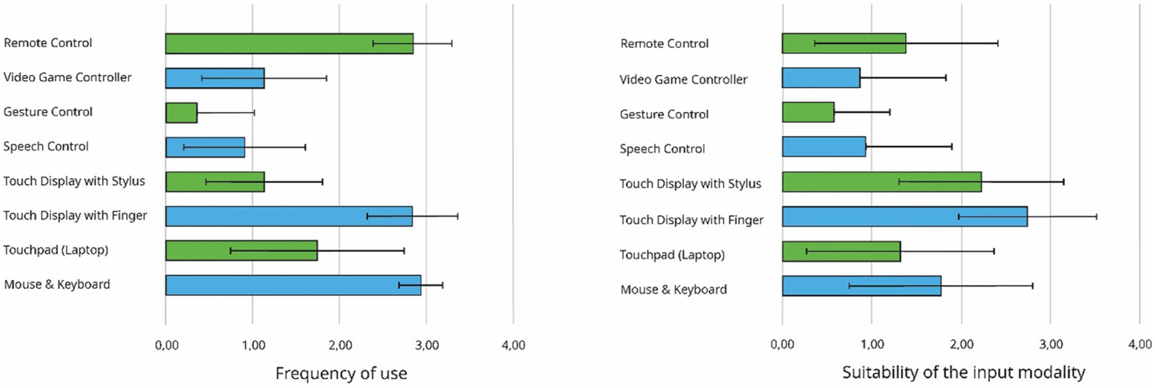


Figure 8: Result of the surveys on input modalities.

Table 1: Coding agenda for the qualitative survey of factory personnel on touch systems.

Category	Definition	Anchor example
1.1 Used devices with touch display at home	Naming of devices with touch display used at home	"I mainly use my smartphone at home."
1.2 Used devices with touch display at work	Naming of devices with touch display used at work	"At work I use a control panel with touch display."
1.3 Used devices with touch display on the road	Naming of devices with touch display used on the road	"In the car I have a navigation system with touch display."
2 Used applications on touch devices	Naming of used applications	"I use WhatsApp."
3 Problems of touch displays	Naming of problems in use	"The control panels hang too high."
4 Suggestions for improvement of touch displays	Suggestions for improvement to facilitate use	"The displays should be better calibrated."

Figure 9 shows on the left side the apps that were mentioned in the interviews and how many of the respondents use them. The right side shows which apps are most frequently used on the smartphone.

3.2 Results of design

After the analysis phase, the design phase is carried out, in which the standards ISO 9241-110, 112 and 13 were applied to

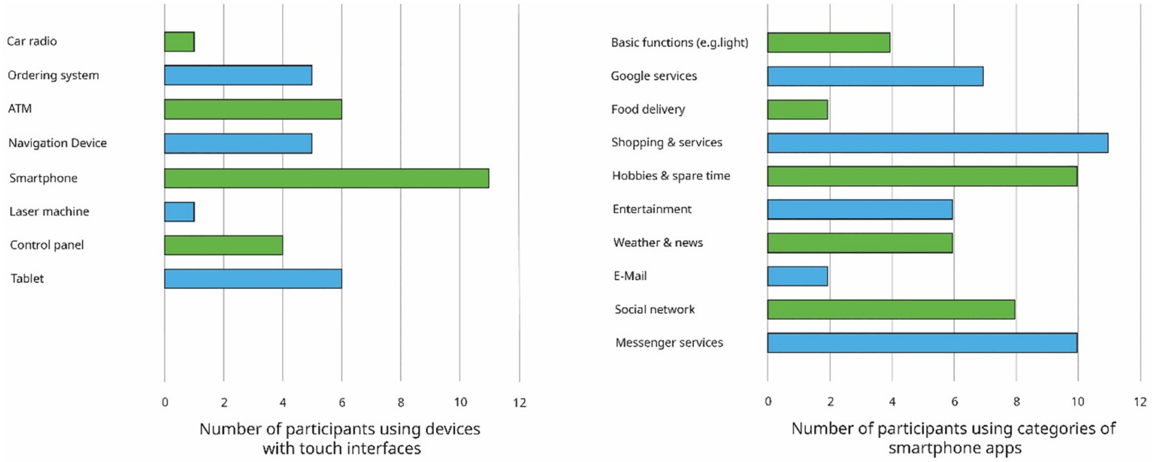


Figure 9: Result of the survey on touch systems.

design the GUI. The principles were systematically applied by looking for application possibilities that proved to be coherent. To illustrate the systematics, the principles were entered in a table and the application of the respective principle in the GUI, as well as a coding, in order to reproduce the application later in the GUI. The coding of the principles consists of the part of the standard (e.g. 110), an abbreviation for the principle created especially for this application (e.g. Ta = Suitability for the Task) and a consecutive numbering starting anew for each principle. Findings from the qualitative evaluation conducted in the analysis phase were also implemented in the GUI. These included, for example, omitting the material from the component description and adding the indication whether fasteners need to be greased.

3.2.1 Design approach by applying ISO 9241-110

The design principles are applied to the GUI of the mobile collaborative robot to create a usable human-robot interaction. The principle of *suitability for the task* was applied by making the button with the robot invisible when robot assistance is not available for the task at hand. Similarly, information about the component is only displayed if requested. In the display for time and tasks, the remaining time and the remaining number of tasks are displayed so that they do not have to be calculated by the worker. The principle of *self-descriptiveness* has been applied to the numbering of tasks, for example, in that the current task is always highlighted in blue in the task bar and is visible in every mode. Completed tasks should be quickly recognized by being colored black. The color red was used for markings to guide the user, such as the motor shaft to be greased. *Conformity with user expectations* was applied by using familiar vocabulary in the checklist, for example. So are generally accepted conventions such as the play button and back and forward buttons familiar from video players and media galleries. Internal consistency of information presentation is implemented through elements that are always in the same place. The principle of *suitability for learning* can be found in that the button at the top left can be pressed for further instructions but does not have to be pressed. In the test window, the user receives explanations through which the system guides the user through the application. Likewise, the system allows the user to retry dialog steps by deselecting buttons from the checklist. In the *controllability* principle, for example, the user controls how a dialog is continued, since switching between tasks is always possible. Likewise, the user controls the speed by being able to pause and restart the robot. The last dialog step can be undone by opening and closing the window, e.g. to confirm a test protocol. *Error tolerance* has been applied by preventing the user from errors by inactive elements. Likewise, the user is supported by a hint he or she receives in case of an erroneous action in the checklist. Activating a confirmation in the checklist can also undo the action if it was not intended. The principle of *suitability for individualization* has been applied, for example, by giving the user the option to select the hint in the upper left corner, but he does not have to. Similarly, the user has the option to choose between different dialog techniques by clicking on the next button or directly on the task. Table 2 shows how the application of the design principles according to ISO 9241-110 was coded and used.

3.2.2 Design approach by applying ISO 9241-112

The 6 design principles for information presentation were implemented in the design as follows. The principle *detectability* was applied by red markings at components, a blue border at the currently visible task on the screen, by flashing the next button and by providing access to information about which actions are possible. The principle of *freedom from distraction* was implemented into the design by grouping the list elements. Likewise by the checklist with red and green buttons, for better differentiation. The display with the remaining tasks and time was implemented with round and square buttons. *Unambiguous interpretability* was applied to the checklist by using known vocabulary for the text. The clear representation of parts was also improved, using a 3-dimensional view. *Conciseness* was applied by a simple representation without unnecessary colors, by possible actions and by a compact alternative possibility to click directly on tasks. The principle of internal and external *consistency* was implemented by familiar elements, such as the Pause button and Back and Forward button as external consistency, but also the consistent arrangement of buttons as internal consistency. Table 3 shows how the application of the design principles was coded and used according to ISO 9241-112.

3.2.3 Design approach by applying ISO 9241-13

The user guidance recommendations have been implemented in the interface using various examples. *Common guidance recommendations* can be found, for example, by hiding the checklist window when the OK button is clicked. Likewise, by using familiar language and vocabular. *Prompts* have been implemented in that the Next button flashes after a task has been completed to prompt for input. The checklist is a specific prompt, since there are

Table 2: Design principles of ISO 9241-110 related to the GUI.

Principle	Application	Code
Suitability for the task	Robot button not visible if robot is not available	110-Ta-1
	Information about component only on request	110-Ta-2
	Remaining time and number of tasks is displayed	110-Ta-3
Self-descriptiveness	Current task is marked blue in the task bar and always visible	110-Se-1
	Completed tasks are colored black	110-Se-2
	User is guided by red markers	110-Se-3
Conformity with user expectations	Familiar vocabulary in checklist (e.g. lubricant, dosage etc.)	110-Ex-1
	Generally accepted conventions through play button like in video player and back and forward buttons like in media galleries	110-Ex-2
	Internal consistency of information presentation through elements that are always in the same place, e.g. servo motor	110-Ex-3
Suitability for learning	System teaches user, as button on top left can be pressed or not	110-Le-1
	System guides through application, by explanation in checklist	110-Le-2
	System allows user to retry dialog steps by deselecting checklist buttons	110-Le-3
Controllability	User controls how dialog continues, since switching between tasks is always possible	110-Co-1
	User controls speed by pausing the robot	110-Co-2
	Dialogue windows can be closed and reopened	110-Co-3
Error tolerance	System prevents user from errors, as inactive elements cannot be pressed, e.g. play/pause button	110-Er-1
	Error management by indication of wrong action in checklist	110-Er-2
	Activation can be undone by confirmation of check in checklist; error correction	110-Er-3
Suitability for individualization	Possibility to select level by hint, which can be viewed, but doesn't have to be	110-In-1
	Possibility to choose between different dialog techniques by clicking Next button or directly clicking on task	110-In-2

Table 3: Design principles of ISO 9241-112 related to the GUI.

Principle	Application	Code
Detectability	Red markings at components	112-De-1
	Blue border at current task	112-De-2
	Flashing of the next button	112-De-3
Freedom from distraction	Task-related information is distinguishable from the background	112-Fr-1
Discriminability	Structuring of information by grouping the list elements	112-Di-1
	Checklist with red and green buttons for better differentiation	112-Di-2
	Round and angular shape of buttons when displaying remaining tasks and time	112-Di-3
Unambiguous interpretability	Familiar vocabulary in checklist	112-Un-1
	Clear representation of parts through 3-dimensional view	112-Un-2
Conciseness	Simple representation without unnecessary colors	112-Conc-1
	Possible actions	112-Conc-2
	Compact alternative by possibility to click on tasks directly	112-Conc-3
Consistency (internal and external)	Known elements pause button and back and forward button as external consistency	112-Cons-1
	Position and layout of different groups always the same as inner consistency	112-Cons-2

only a limited number of input options, namely Confirm and Non-Confirm. The recommendation *feedback* was applied by opening the robot window immediately after clicking. Likewise, the Pause button becomes the Play button after clicking. The task page and button change after clicking. The *status information* recommendation is applied by displaying the task progress in the task bar, displaying the number of remaining tasks and the remaining time, and displaying the robot progress in the robot view. The recommendation *error management* has been applied by displaying a hint on what to do when the Non-Confirm button is clicked. Similarly, there is an error handling by the user by undoing or deselecting the confirm button of the checklist. *On-line help* is found in the checklist by appearing the hint to assist in

Table 4: Design principles of ISO 9241-13 related to the GUI.

Principle	Application	Code
Common guidance recommendations	Window can be closed and reopened on demand	13-Co-1
	Terms like *lubricant* and *dosage* are typically used by workers	13-Co-2
Prompts	Click the button that flashes, as explicit input	13-Pr-1
	Specific input prompt, as limited number of input possibilities	13-Pr-2
Feedback	Window opens after click	13-Fe-1
	Pause button becomes Play button when clicked	13-Fe-2
	Task page and button change after click	13-Fe-3
Status information	Progress of tasks	13-St-1
	Number of remaining tasks and time left	13-St-2
	Progress of the robot	13-St-3
Error management	Hint appears when checkbox is clicked	13-Er-1
	Error handling by user, clicking can be undone	13-Er-2
On-line help	Hint appears in checklist	13-On-1

accomplishing the task. Table 4 shows how the application of the design principles according to ISO 9241-13 was coded and used.

3.2.4 Design result of the interactive mockup

The design of the interactive mockup is illustrated in Figure 10. The definition of each term for the GUI is described as follows.

1. The Resource button is visible when the overall goal view is displayed and is selected to get details about the execution of the task.
2. The Robot button changes from the overall goal view to the robot view and becomes the overall goal button to return to the overall goal view.
3. The Checklist button is visible in both the overall goal view and the robot view and calls up the checklist.
4. The Back button leads to the previous task and is not present when you are at the first task.
5. The Next button leads to the next task and is not present if you are at the last task.
6. The Pause button stops the robot and can be activated once the robot has started its task. Once it is pressed, the robot stops and the Pause button becomes a Play button. When pressed, the Play button starts the robot again and becomes a Pause button.
7. Task bar with Task buttons; the Task buttons call up the respective task page when clicked; the view can be switched between the tasks at any time.
8. The task display shows the remaining number of tasks.
9. The time display shows the remaining time until the task has to be completed.
10. The assembly display is visible in the overall target view and shows the current assembly that has to be completed.
11. The robot status window shows which task the robot is currently performing and how far it has progressed with this task.

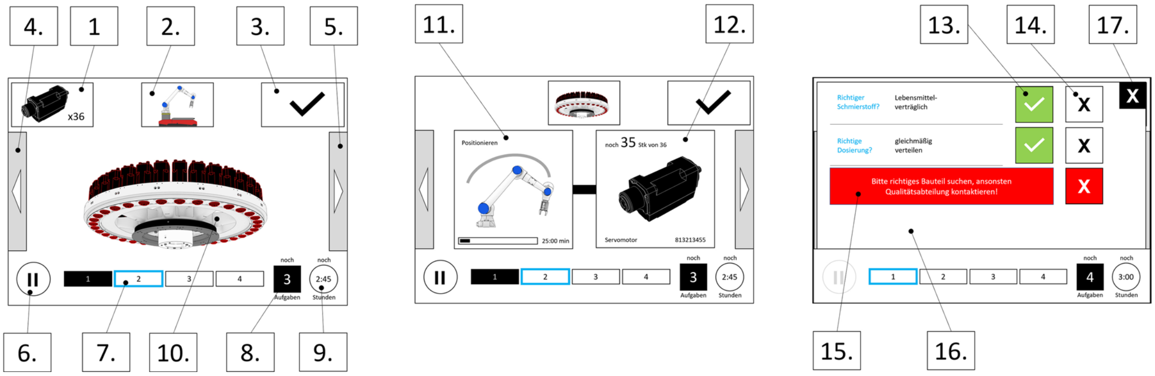


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Figure 10: Control and display elements of the GUI.

12. The equipment status window shows which equipment the robot is currently assembling and how many elements of it are still to be assembled. The equipment is also displayed graphically with its part number.
13. The Confirm button confirms that a task has been performed correctly. If it is clicked again, the button will be inactive again.
14. The Non-Confirm button should be clicked if a specification of a task was not correctly executed. If clicked again, the button will be inactive again.
15. The checklist message text appears as soon as the Non-Confirm button is clicked. When the button is clicked again, the text disappears.
16. The checklist is a dialog box that appears when the Checklist button is clicked. In it, the compliance of the task must be confirmed in order to complete a task.
17. The Window Close button closes the checklist again when clicked.

The principles used from the three parts of ISO 9241 are illustrated in the mockup of the GUI. Here, application cases, but also overlaps or repetitions of the principles become visible. The individual parts of ISO 9241 were colored in three colors in order to be able to distinguish them easily. ISO 9241-110 was colored red, ISO 9241-112 was colored blue, and ISO 9241-13 was colored green. Figure 11 shows the overall goal of the work task where the assembly is visible. It has already been stated that the GUI needs a representation of the overall goal, which is the result, the necessary component and a status bar with the overview of the number of tasks and time. The required component is displayed in the button in the upper left corner of the GUI. It can display additional information at the click of a button as a support for the task execution. According to the principle suitability for the task the display is optional, because an experienced worker does not need the information. The same result of the design comes out if the principle suitability for learning is applied as well as the principle suitability for individualization. The blue marking of the current task results from the application of the principle self-descriptiveness. The same result is obtained by applying the feedback recommendation. According to the principle controllability, the display of a task results by clicking the numbered button of the respective task. The same result is produced by the conciseness principle. It considers the mapping with the overall goal of the user interface. As an example, three design principles of ISO 9241-110 have been applied to the resource button. The result is a button that should be selected first to get more detailed information about the current task.

The illustration with the robot activity of the GUI is considered. Several design recommendations act on elements like the Back and Next button. Suitability for individualization leaves the freedom to choose the task. Detectability

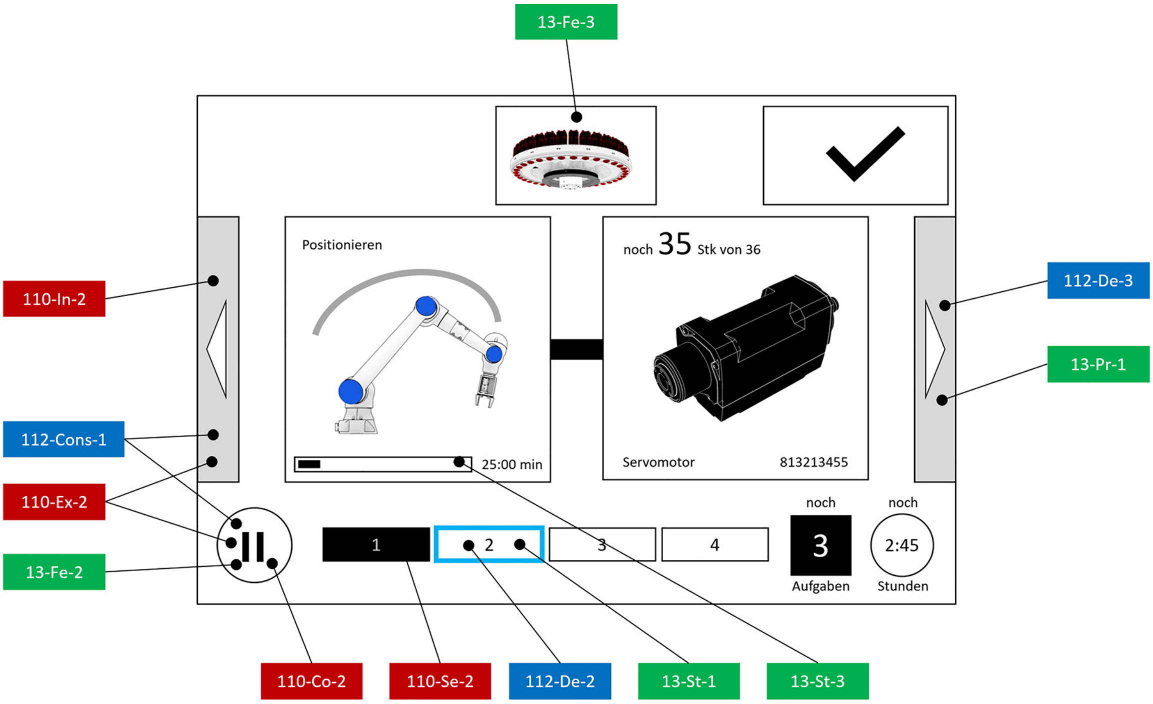

Figure 11: Overall goal of the assembly.

makes the design easily recognizable. Prompts lead to a blink to promote clicking on the next task. Conciseness recommends simple presentation. Conformity with user expectations recommends a familiar design, e.g. as with media galleries. Figure 12 shows the status of the robot related to its current activity.

The illustration with the checklist is considered (see Figure 13). The checklist message contains several design principles. The *suitability for learning* principle results in the solution that the system guides through the application by means of explanations in the checklist. This can also be seen as *error tolerance* since hints are displayed in case of an incorrect action. The *error management* recommendation is also applied, as support is provided to deal with failure to complete the task. *Unambiguous interpretability* is employed through known vocabulary that is used. It can be seen that there are some redundancies in the design of the hint text as far as the use of design principles is concerned.

The insight is forming that several design recommendations can relate to the same element. Nevertheless, each recommendation has a different influence on the element. Thus, shaping, coloring, word finding, or animation (e.g., blinking) are influenced. Although there are redundancies in the application of recommendations to individual elements (e.g., *error tolerance* and *error management*), there are no indicators of which recommendations are particularly relevant and which are redundant.

3.3 Results of evaluation

3.3.1 Result of heuristic evaluation

The heuristic evaluation produced a total of 40 different suggestions for improvement. One suggestion was mentioned by three experts independently of each other. Namely, a documentation or tutorial should be displayed at the beginning to introduce the user to the GUI. Seven suggestions were made by two experts independently of each other. These included setting tasks interactively if they cannot yet be edited. Or adding the note “Activate robot”, avoiding dialog boxes and providing space for error messages. 32 suggestions were made by only one person at a time. These include having the lubricant material number noted, putting more information in the center of the screen that is associated with the part, or better highlighting statuses when the task is completed.

3.3.2 Result of situation awareness evaluation with controlled experiment

The overall performance of the controlled experiment is $M = 0.92$ (SD = 0.08). For assignments related to the task it is $M = 0.93$ (SD = 0.08), for assignments related to the robot it is $M = 0.87$ (SD = 0.07). These are very high values for a first interactive mockup and indicate that the acquisition

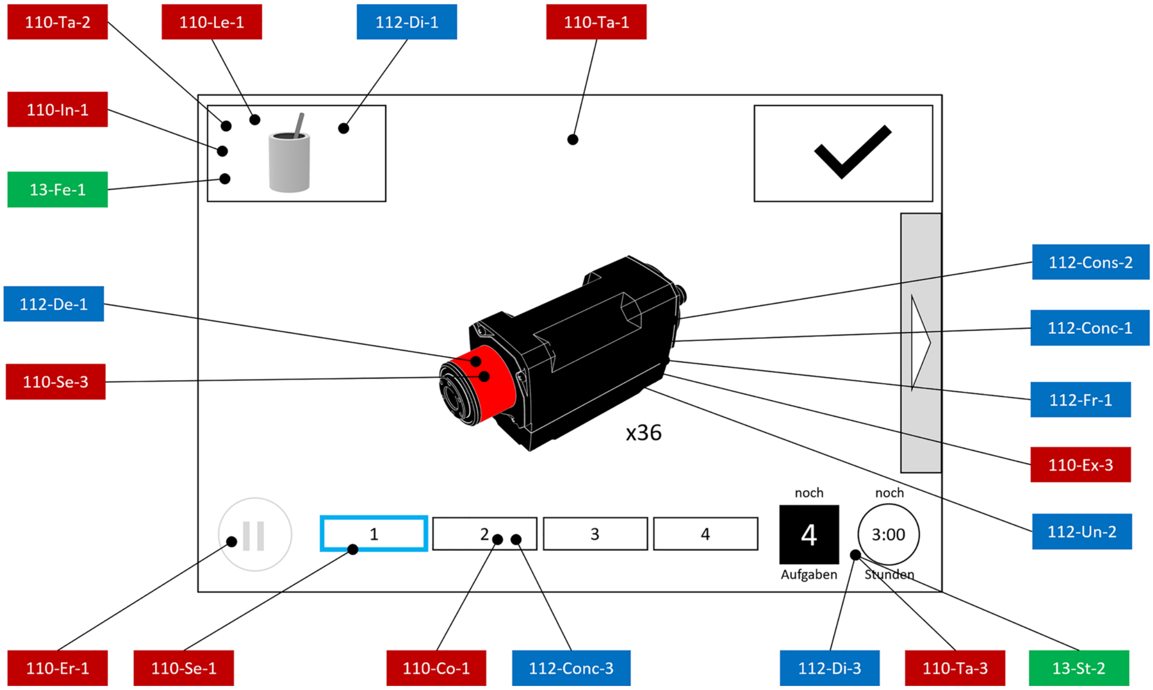

Figure 12: Status of the robot related to its current activity.

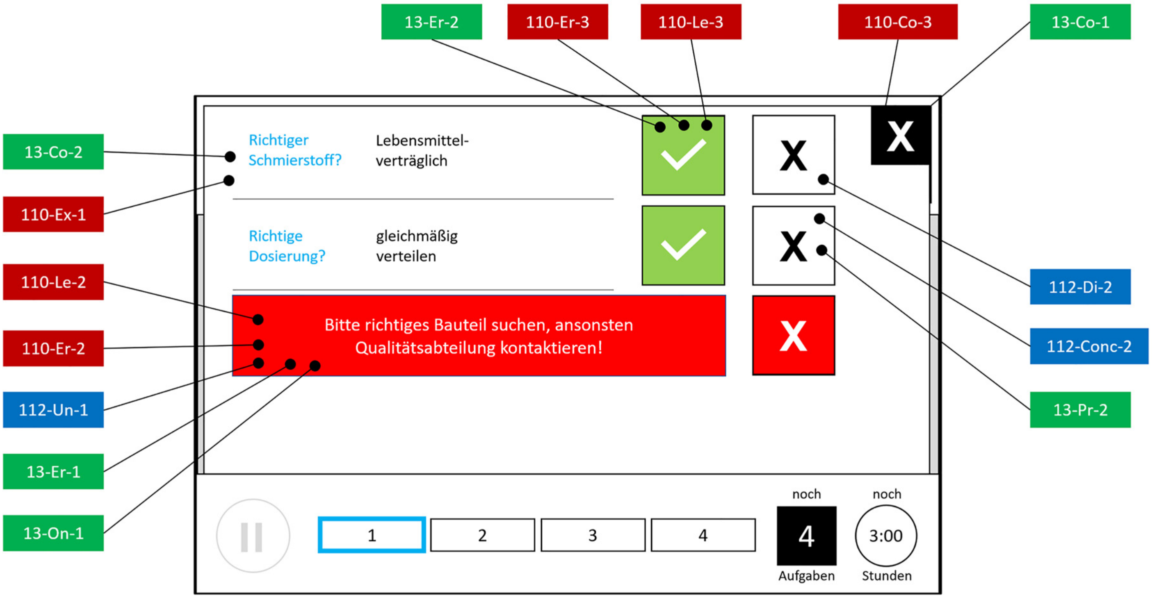

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Figure 13: Checklist window to verify that the current task is being performed correctly.

of information was extremely positive. Overall situation awareness is at a value of $M = 0.83$ (SD = 0.20), which is also a high value. This indicates that the information displayed on the user interface is not only easy to grasp, but also useful, thus supporting situation awareness. This applies both to the awareness of the task, whose value is at $M = 0.82$ (SD = 0.20), and the awareness of the robot, whose value is at $M = 0.84$ (SD = 0.20). Figure 14 shows the results of the measurement for situation awareness, divided in a performance boxplot and situation awareness boxplot. The assignments were solved well, the worst performance was in assignment 6, where only about 73 % of the participants solved it. Situation awareness was also quite high across the assignments. There is no significant mean difference between TA and RA assignments in performance or situation awareness. However, descriptively it can be seen that the mean value of performance is somewhat higher for TA assignments and situation awareness is higher for RA assignments, which could possibly have something to do with the new and unfamiliar assignments in connection with the robot.

4 Results of second iteration

4.1 Results of design with high fidelity mockup

The second iteration of the design implemented the results from the previous phases. These include the recommendations from the heuristic evaluation and the measurements for situation awareness. Similarly, for a holistic approach to interface design, the intuitive robot programming designed

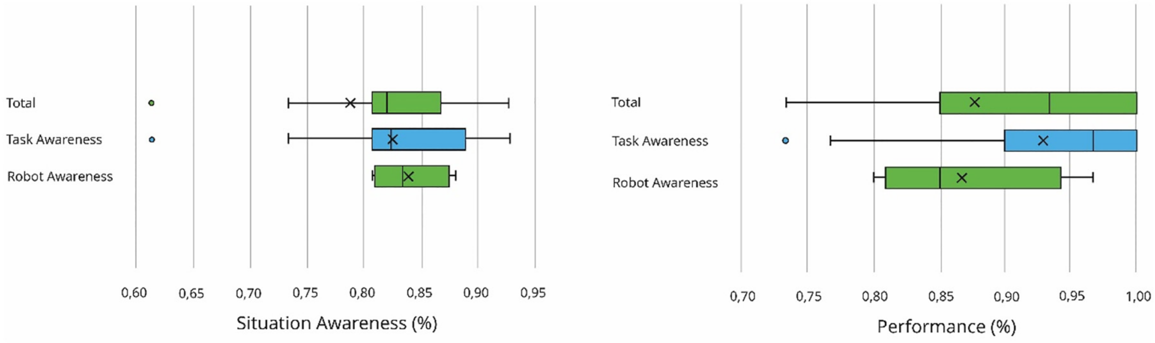

Figure 14: Results of the measurement for performance and situation awareness.

and evaluated in another study is integrated into the design. In the measurements for situation awareness, feedback recorded in the form of comments from the subjects was also implemented in the GUI. Here are a few examples of this: In both the heuristic evaluation and the feedback for the situation awareness measurement, it was recommended to add the name of the lubricant. Feedback from the situation awareness measurement, for example, is that the lubricant dosage is better represented. This was resolved by adding a short instructional video that can be played in the interface. The wish to have text descriptions for the images was also mentioned as feedback by test persons. Buttons were made more prominent, using contrasts and shadows. Simple changes suggested by some workers that sounded coherent were implemented in the design, such as a red drop to clearly mark lubricants. In the heuristic evaluation, a suggestion was also made by one person. The current task of human and robot was displayed more concisely and the status of the robot was made visible at any time. An added function, which was also proposed in the heuristic evaluation, is the manual control of the robot. It switches to a mode in which the robot can be controlled via teleoperation. Figure 15 shows two views of the GUI as an example.

Due to the implementation of desired functions, the interface has become visually more complex at the same time. This has made it necessary to cluster it into three sections. These three sections have been colored for better distinction. The upper section is the menu bar, which is colored blue. It contains the main buttons menu, manual control, current job number, programming mode and the help button. The middle section is colored light gray and contains basically the same elements as in iteration 1. Some information has been added, such as text information, which is why the buttons themselves are distinguished from the light gray background by a white coloring. The bottom section is colored medium gray and contains information about the robot (battery level and activity), information about the work task (completed tasks and current task allocation), and the status of the overall goal (number of completed and uncompleted tasks, expected completion of tasks). Colors were applied even more clearly for marking, as recommended in the Heuristic Evaluation. Thus, a high battery level of the robot was marked with a green bar and a completed task was colored green in the lower section. Status elements that should basically be easily recognizable were colored dark blue. For example, the active robot status and the active work task in the lower section. Important information concerning the current task is colored red, e.g. the area to be greased. The programming mode is almost identically executed as in the previous research on user-centered design for intuitive robot programming. Only the menu has been placed on the left instead of on top, because there is already a menu bar on top. Basically, in the high fidelity mockup, several pieces of information have been stored at each button to retrieve details on demand, e.g., about robot status, task status, and components to be inserted. Figure 16 shows a detail view of the robot status and a view of the robot programming mode.

4.2 Results of the usability test with end users

The results of the usability test were recorded in a table. The highest values were obtained by the interaction principles *suitability for the task* ($M = 2.23$; $SD = 0.82$) and *suitability for learning* ($M = 2.11$; $SD = 1.01$). Behind them are the principles *self-descriptiveness* ($M = 2.00$; $SD = 0.81$). Likewise, *conformity with user expectations* ($M = 2.09$; $SD = 0.79$) produced a good result, although it has a slightly lower

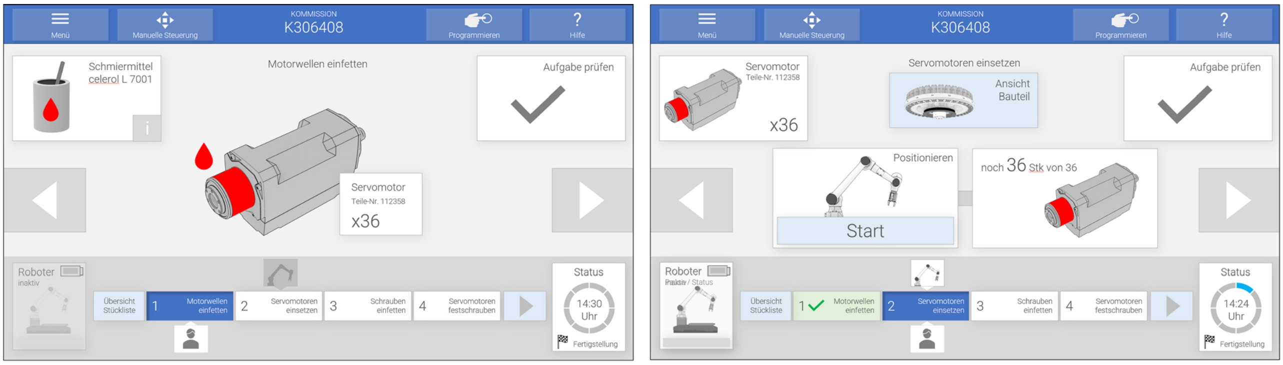

Figure 15: Second iteration of GUI design – the left view shows the greasing task of the servo motors, the right view shows the support by the robot when inserting the servo motors.

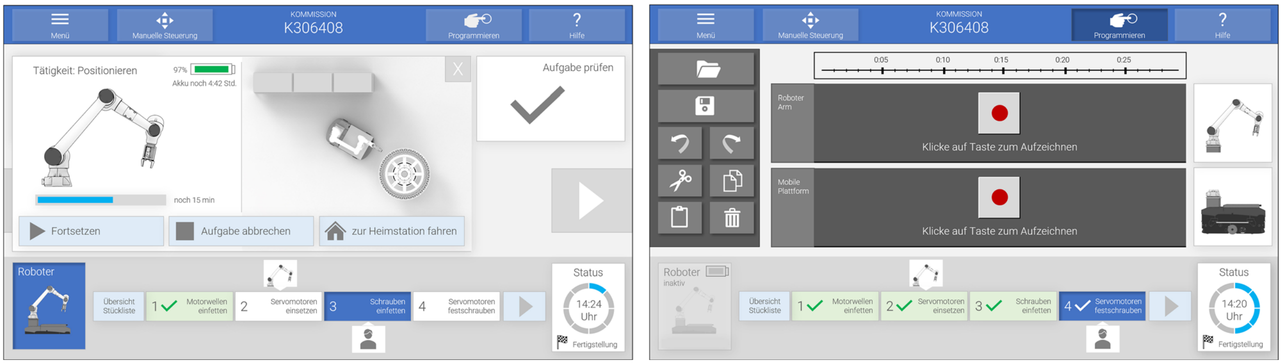

Figure 16: Second iteration of GUI design – the left view shows the robot status, the right view shows the programming mode.

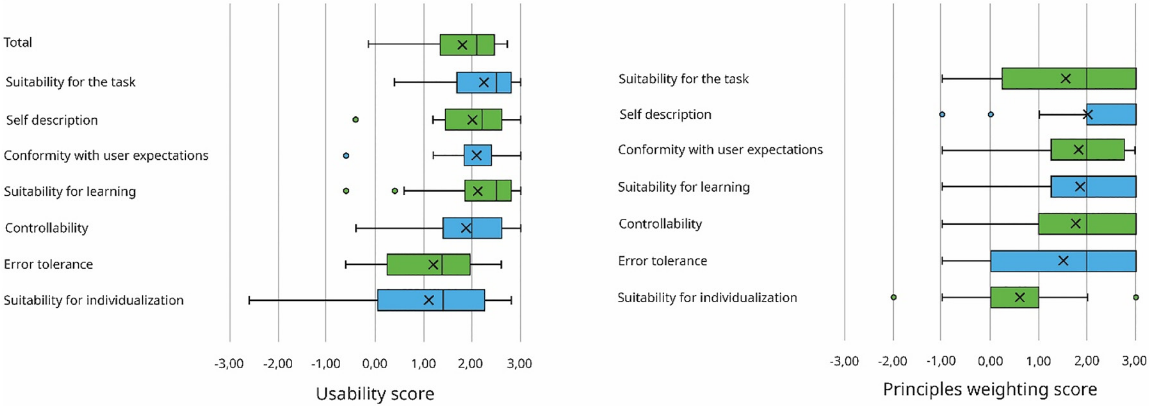

Figure 17: Result of the usability test and principles weighting.

rating. The interaction principles *error tolerance* ($M = 1.19$; $SD = 0.96$) and *suitability for individualization* ($M = 1.11$; $SD = 1.32$) produced the lowest results. In the case of *error tolerance*, there are fewer positive evaluations because no real error messages or other problems with the system occurred in the mockup. In terms of *suitability for individualization*, the mockup also did not place much emphasis on the customizability or editability of the system. This was not considered negative by the test persons, but rather neutral. The overall score of $M = 1.8$ ($SD = 0.77$) is relatively good. Regarding the importance of the principles for the use case, the principles *self-descriptiveness* ($M = 2.06$; $SD = 1.18$), *suitability for learning* ($M = 1.88$; $SD = 1.15$), *conformity with user expectations* ($M = 1.81$; $SD = 1.11$) and *controllability* ($M = 1.81$; $SD = 1.33$) are seen as particularly important. *Error tolerance* ($M = 1.56$; $SD = 1.41$) and *suitability for the task* ($M = 1.5$; $SD = 1.32$) are rated somewhat less important. The principle *suitability for individualization* ($M = 0.63$; $SD = 1.50$) appears to be rather unimportant. The high variance for the factors can probably be inferred from the fact that certain factors were not assigned a high weighting in the design of the GUI (e.g. suitability for individualization). Likewise, the testers have different perceptions of the factors. Since these are subjective judgments that are entered by the participants in the questionnaire but not reasoned, these questions remain unanswered. Figure 17 shows the result of the usability test and the weighting of the design principles.

5 Discussion

5.1 Interpretation of results

The goal of this research is to develop a combination of methods for a user-centered design process – implemented as an interactive mockup – that considers situation awareness and usability in a mobile HRC at assembly workplaces. The choice and combination of existing methods for user-centered design are enormously diverse and always context-dependent, and this research specifies a combination of methods for designing GUIs in this under-researched field. While there are a variety of related works, this work describes the approach of a design process in detail with exemplary methods. The process of user-centered design was conducted in two iterations, consisting of analysis, design, and evaluation in the first iteration. In the second iteration it consists of design and evaluation. The iterative design process applied like for the mobile assistance system [22] has enabled fast feedback loops and insights. The control loop model for human-centered HRC [16] is also applicable to the context of mobile HRC, since the mentioned components “human”, “robot” and “user-centered design process” fit to this research. The model can be seen as equivalent to the iterative process. The categorization of the phases into analysis, design and evaluation compared to the research on user interfaces for HRC at production workplaces [19] was also used in this work and has shown to be reasonable. A wireframe developed in advance was used as the basis, which was designed with a focus on situation awareness. To achieve a user analysis, two surveys were conducted in the first step. The first was a quantitative survey to query known and desired input modalities of the GUI. The second was a qualitative survey to identify relevant information about awareness and satisfaction of touch interfaces by the respective target group of assembly workers. The first survey produced quite unambiguous results that touch interfaces are most likely to be imaginable. The subsequent qualitative questioning about touch interfaces only led to the fact that nearly all interviewees are aware of devices with touch interfaces and that the greatest satisfaction exists with smartphone apps. For the analysis phase, it is noticeable that none of the related works has performed a user analysis, though it has been shown in this research to be an important approach to understand users. In the second step, the design phase, an interactive mockup was developed. This research not only mentions the fact that ISO 9241-110 has been applied like in related work about service robots [14, 15], but precisely names the principles applied and extends the application to include parts ISO 9241-112 and 13, as recommended in ISO 9241-210. It has been shown that the principles are basically a good and important aid, which can also be transferred to the GUI for mobile HRC. The examples in the standard were originally intended for the context of computer workstations, and this can often be read out. A certain amount of creativity and experience regarding usability is necessary to transfer the abstract formulations of the principles to the context of mobile HRC. After applying several parts, a redundancy is noticeable at some point, because several design principles lead to the same design feature. A scheme of which principles are redundant was not investigated. Future work can take up this aspect and investigate it systematically. By applying the design principles from ISO 9241, a GUI has basically been designed that promotes usability. Situation awareness is not considered in the standard and could only be achieved through the preliminary work of the wireframe. The approach, consisting of Goal-Directed Task Analysis as well as design principles for situation awareness, is essential. Another evaluation with the interactive mockup was the heuristic evaluation according to Nielsen, carried out with usability experts. Compared to the generally held design principles, the heuristic evaluation was able to identify concise suggestions for improvement. It has proven to be an economical evaluation method like reviewed in the literature [23, 24]. With the interactive mockup, a measurement of situation awareness could be conducted, which on the one hand showed that the interface leads to high situation awareness, and on the other hand, suggestions for improvement could be collected from end users. The suggestions of the usability experts partly overlapped with the feedback from the end users during the evaluation for situation awareness. From the variety of methods to measure situational awareness [28–31], the SAGAT method was modified to include a 6-point Likert scale, which proved to be a valid approach. The first iteration was completed with the evaluation phase to get early feedback that was implemented in a high fidelity prototype.

In the second iteration, findings and suggestions for improvement from the evaluations were implemented in the high fidelity GUI design. Likewise, the mode for intuitive robot programming was integrated. The holistic approach consists of the joint assembly of components as well as the possibility to independently program new steps during the assembly. The mode for intuitive robot programming was indicated by means of an exemplary screen and was not evaluated further in the usability test, since extensive end-user tests had already been carried out in the preliminary study for intuitive robot programming [32]. It was only relevant that the test persons understand how to get into the programming mode, how it compares to the HRC working mode, and for what purpose there is a programming mode that workers can operate. The evaluation of the high fidelity mockup was done by a usability test using the standardized questionnaire ISONORM 9241/110, which is based on the design guidelines of version 2006 of the corresponding standard, therefore this version of the standard was also used for the design. An application of the questionnaire System Usability Scale compared to the wheelchair robot GUI [17] and the mobile robot for elderly care [18] would be also an alternative in this work. However, the questionnaire ISONORM 9241/110 asks exactly for the principles of the applied standard. The taxonomy with the collection of usability methods [26, 27] was helpful to get an overview, but it is not immediately obvious which methods should be used for which context. This should be done intuitively because success of a method only becomes apparent during evaluation.

To gain more insight into the conceptual design of the process itself, this can be described as follows. The design process was developed step by step related to the phases. The preliminary research [33] contained a Task Analysis (Goal-Directed Task Analysis and Physical Model) and design principles for situation awareness, where design and evaluation insights were used to develop an interactive mockup. The mockup from iteration 1 was the precondition to measure situation awareness and evaluate usability. Therefore, information about the users was gathered, including their known and desired input modalities for devices. Following this, design principles for usability provided by ISO 9241 were implemented, as they are one of the most prominent principles in this field. Insights for usability and situation awareness were the outcomes of the evaluation, gained by the inspection method of heuristic evaluation and the situation awareness evaluation, which contained also constructive feedback from the workers. This has paved the way for a holistic design in iteration 2, realized by the high fidelity mockup, where also design and evaluation insights for intuitive robot programming were implemented. The mockup was subjected to a usability test with potential end users, requiring higher effort and involvement than inspection methods. Figure 18 shows the historical development of the GUI. On the left side the wireframe design is shown, in the middle the interactive mockup and on the right side the high fidelity mockup.

The very good results of the usability test with end users indicate that the selected preceding process phases have led to an optimization of the user interface. It opens up that the application of the methods used here would also lead to a successful result if applied again in a similar context. This would provide generalizability. While several works on mobile HRC are technology oriented [11–13, 20], this work refers to a user-centered design and fills the research gap to identify methods along the entire design process that lead to optimized user interfaces.

5.2 Limitations

As mentioned before, the present work has an intuitive approach to design the GUI. It has produced satisfactory results. But it does not exclude whether there are more suitable methods for carrying out the design process. To explore the optimized approach, methods would have to be compared directly. Likewise, no other parts of DIN EN ISO 9241 were applied, as recommended in DIN EN ISO 9241-210, because they would go beyond the scope of this work. What difference the design would make without design principles was not investigated. Usability experts who have experience in GUI design are basically familiar with the design principles of ISO 9241-110. The experiment would have to be conducted with people who have no experience in designing interfaces. When measuring situation awareness, despite

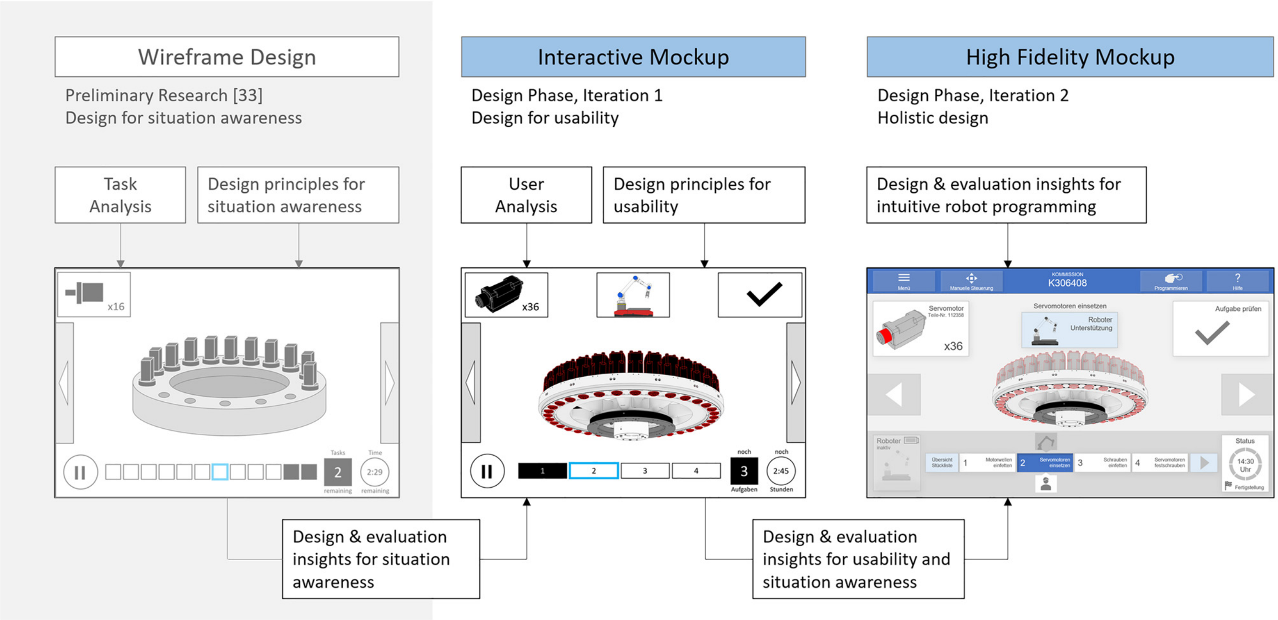

Figure 18: Historical development of the GUI.

the very good results, several influencing factors may have caused the evaluation to be favored. For example, the questions could be too similar to the terms on the GUI, e.g. “dosage”. The limitation to four tasks may have simplified the application and information absorption. The fact that the tester did not actually perform the task might have given him more thinking time and foresight. Further research can include these aspects.

6 Conclusion and outlook

In this article, an approach was described to develop a user-centered design of a GUI for mobile HRC that supports situation awareness and promotes usability. The study was conducted in response to the current shortage of skilled workers in production and construction. The goal was to apply a combination of existing methods to a user-centered design process in order to obtain a GUI that supports workers in assembly tasks. This involved researching an overview and taxonomy of methods, as well as picking up methods from related, similar work and applying them to this context of HRC for an assembly workplace. The development was conducted in two iterations consisting of analysis, design, and evaluation phases. The designed mockups were evaluated through heuristic evaluation, situation awareness measurement and usability testing. The results indicate that the approach can lead to user-centered GUIs with high situation awareness and usability. As an outlook, the method combination can be applied on similar use cases to prove generalizability. The scientific value is that the relatively new field of mobile HRC in industry will find more acceptance if the GUI is designed user-centered by consideration of situation awareness and usability. The research gap that has been filled in this work is the exploration of which combination of methods leads to satisfactory results in a user-centered design of a GUI for mobile HRC.

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Informed consent: Informed consent was obtained from all individuals included in this study, or their legal guardians or wards.
Author contributions: The authors have has accepted responsibility for the entire content of this manuscript and approved its submission.
Competing interests: The authors states no conflict of interest.
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Data availability: The raw data can be obtained on request from the corresponding author.

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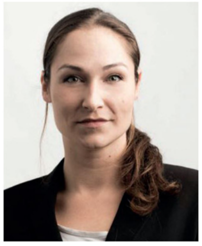

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