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How to include User eXperience in the design of Human-Robot Interaction

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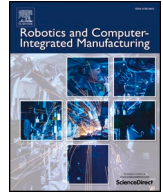
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## Proof

## How to include User eXperience in the design of Human-Robot Interaction

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## ABSTRACT

In recent years Human-Robot Collaboration (HRC) has become a strategic research field, considering the emergent need for common collaborative execution of manufacturing tasks, shared between humans and robots within the modern factories. However, the majority of the research focuses on the technological aspects and enabling technologies, mainly directing to the robotic side, and usually neglecting the human factors. This work deals with including the needs of the humans interacting with robots in the design in human-robot interaction (HRI). In particular, the paper proposes a user experience (UX)-oriented structured method to investigate the human-robot dialogue to map the interaction with robots during the execution of shared tasks, and to finally elicit the requirements for the design of valuable HRI. The research adopted the proposed method to an industrial case focused on assembly operations supported by collaborative robots and AGVs (Automated Guided Vehicles). A multidisciplinary team was created to map the HRI for the specific case with the final aim to define the requirements for the design of the system interfaces. The novelty of the proposed approach is the inclusion of typically interaction design tools focusing in the analysis of the UX into the design of the system components, without merely focusing on the technological issues. Experimental results highlighted the validity of the proposed method to identify the interaction needs and to drive the interface design.

## 1. Introduction

In the context of Industry 4.0 (I4.0), machines are becoming "intelligent" and more and more robots are being added to the workforce to improve the process quality and productivity. In fact, robots represent one of the nine pillars of I4.0 [1]. However, humans are still necessary to guarantee high process flexibility and to proactively respond to the evolving market needs and to ever-increasing requests for product customization. In this context, smart factories need not only robots but also a strong collaboration between robots and humans. Based on this, the so-called Human-Robot Collaboration (HRC) is one of the main topics of research for the new smart factory. Indeed, in modern smart factories humans and robots have to coexist in a common workplace: robots can complement the humans' sensory, physical and cognitive characteristics, while humans can take care about the more delicate and cognitive tasks. Moreover, robots should be designed to properly assist human workers in performing a certain task in order to obtain greater efficiency and effectiveness.

Human-Robot Interaction (HRI) has emerged as a specific research field during the early 1990s. It is based on understanding, designing, and evaluating robotic systems for use by or with humans, to finally understand and shape the interactions between one or more humans

and one or more robots, as defined by Goodrich and Schultz in [2]. HRI is also the science of studying how people interact with robots, focusing on their behaviour and attitudes towards robots in relationship to the physical, technological and interactive features of the robots [3]. In a nutshell, the final aim of HRI is to develop not only time efficient robots, but also robots acceptable to people, able to meet the social and emotional needs of their individual users as well as respecting human values. For this purpose, HRI covers several research areas such as engineering, technology, psychology, design, anthropology, sociology, philosophy [4,43]. All these disciplines are important to develop a successful human-robot interaction, considering the technological limitations and respecting the humans' needs. Each discipline faces the topic in a different way and analyzes different aspects of the human-robot interaction.

Nowadays, interaction and collaboration between humans and robots are open issues in any application context (from industry to healthcare, surgery, urban search and rescue, defense, until personal services), but particularly in the manufacturing area. Indeed, there are numerous advantages linked to the evolution of manufacturing processes with the introduction of robots and the collaboration with humans. The first reason to include robots in manufacturing is to lighten human physical and cognitive efforts. For this purpose, the operator's

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activities should be re-organized in order to assign more cognitive and control tasks to humans, and to assign repetitive tasks and all operations that require greater accuracy, speed and repeatability to robots [5].

Roughly speaking, most of the industrial and scientific research on HRI and HRC is today strongly “robot-centered”, focusing mainly on technical issues and technological solutions, without reasoning on the human perspective. Some works deal with the technical design of specific collaborative robots’ applications [6], or of physical components of the robot to allow visual communication [7], others on new intelligent programming methods (e.g. walk-through programming [8], programming by demonstration [7]). Human safety is often taken into consideration, mainly facing the issues linked to the human-robot coexistence in a cell [9]. Moreover, a recent study concerns how to adapt the robot’s behavior to lighten the burden on the operator and to comply to his/her needs [10].

Conversely, this research focuses on the human side of human-robot collaboration and put the humans at the center of the human-robot system design, according to the Human-Centered Design (HCD) approach. Regardless of the specific task performed, robots are designed to support humans. Thus, it is not possible speaking of robots without considering them in relation with humans. As a consequence, Human Factors should be taken into consideration throughout the in human-robot interaction design process. The adoption of the human’s point of view allows to foresee the user’s needs, behavior and sensations during the interaction with robots, with the final aim to build up a solid knowledge about the user to design a better user experience.

The paper adopts a human-centred approach and presents a structured methodology for the design of the HRI, primarily focused on the detailed knowledge of the communication exchange between humans and robots. The first aim of this research is to demonstrate how a human-centered design approach can be effectively applied on HRI. Moreover, this research aims to identify a set of guidelines for the design of human-robot interfaces, with particular attention for the manufacturing sector.

## 2. Related works

### 2.1. HRI in manufacturing

Collaboration between humans and robots includes interaction and all related actions that create a direct communication flow and a common understanding between humans and robots, jointly performing a certain task. It is defined also as a state where human beings (operators or simple users) cooperate with purposely designed robots to work together within a defined workspace. In particular, Human-Robot Interaction (HRI) is a general term to refer to all forms of interaction between human and robot [11]. As a consequence, Human-Robot Collaboration (HRC) can be considered as a subcategory of HRI, as it takes place into a specific collaborative workspace, as the space within the operating space where robots and humans can perform tasks concurrently. According to Thrun, collaborative robotic technologies can be grouped into three main categories: industrial robotics, professional service robotics, and personal service robotics [12]. In contrast to robot manipulators, which are mainly passive and do not employ sensors and actuators, collaborative robotics is made up of flexible and “intelligent” devices to allow a direct interaction with the user, creating a sort of “dialogue” with him/her to support the human activity using different kind of technologies (e.g. sensors, actuators and data processing) [13].

HRI is today applied in many contexts, from industry to healthcare, defense, until personal services. In particular, the manufacturing context offers many situations of co-presence of humans with robots. The relationship of humans and robots in a shared work environment is a many-faceted phenomenon which is classified according to a number of different viewpoints, also according to the specific context of application. As far as industrial applications are concerned, four criteria can be

defined for decomposing human-robot interactions, according to [14]: workspace, working time, aim, and contact. The workspace could be collocated or non-collocated as the working time could be synchronous or asynchronous [9,15]. In the same way, also the aim of operator and robot can be shared or not, and contact between humans and robots can take place or not [15]. The classification of the human-robot relationship can also consider other parameters such as shared resources (i.e. physical, cognitive or computational) and the presence of multiple robots and humans, considering also their respective role [16]. On this basis, numerous combinations of the human and robotic agents are possible. The highest level is the so-called symbiotic collaboration, which takes place when human and robots coexist in a physical space to interact with each other so as to solve hard tasks requiring a significant mental and computational effort [16].

On the basis of the above-mentioned criteria, HRI has been classified into three areas, adapted from [14]:

- Human-Robot Coexistence (common workspace and time, sequential tasks on common resources or simultaneous tasks on different resources between humans and robots);
- Human-Robot Cooperation (common workspace, time and shared aim, tasks can be sequential or simultaneous on same resources without a direct contact);
- Human-Robot Collaboration (common workspace, time, for a shared aim, tasks can be sequential or simultaneous on same resources with a direct physical contact).

This classification is valid also in those contexts where multiple humans or multiple robots are involved.

As a consequence, the substantial difference of HRC with respect to HRI is the sharing a common goal and having a direct contact. It implies that humans and robots have to share their skills to solve a specific task, in a collaborative way. The ISO 10218-1 defines Collaborative Robots as robots designed to physically interact with humans in a shared workspace [17]. The potential of HRC is the combination of the robot features (e.g. adaptability, accuracy, speed) with the properties of the human cognitive skills (e.g. problem solving). To facilitate this collaboration, humans has to work and interact with the robot safely. Furthermore, the robot must adapt to the human behavior and foresee the humans’ needs.

In any cases, collaboration implies a deeper interaction between humans and robots. In this context, interfaces play a central role, as the main communication channel between the two entities involved (i.e., humans and robots). A key aspect in collaboration is interaction. Talking about interactions also means talking about interfaces. A high-quality Human-Robot Interaction (HRI) requires intuitive user interfaces. On one hand, the operator can give to robot inputs in a simple way, without any distraction from his/her main task; on the other hand, the robot provides clearer information to the user, generating an immediate comprehension and data interpretation. Adopting intuitive interfaces becomes even more important in the case of a close collaboration between robots and humans. In a HRC scenario, humans and robots combine their respective skills to carry out a common task in the most efficient and effective way. Based on this, the human-robot communication should be natural and spontaneous as between humans. For this purpose, a detailed knowledge on human-centred interface design is required.

Interfaces can, indeed, generate different kind of communication: from graphical language to voice-based communication, until gesture-based dialogue. Also, the types of interfaces consequently change. For instance, graphical communication can take place either using specific devices (e.g., monitor, touchscreen), while voice-based communication can use Natural Language Interfaces (NLI) and gesture-based communication can use proper cameras to track the human’s hands [8]. According to the communication typology, human-robot interfaces can be

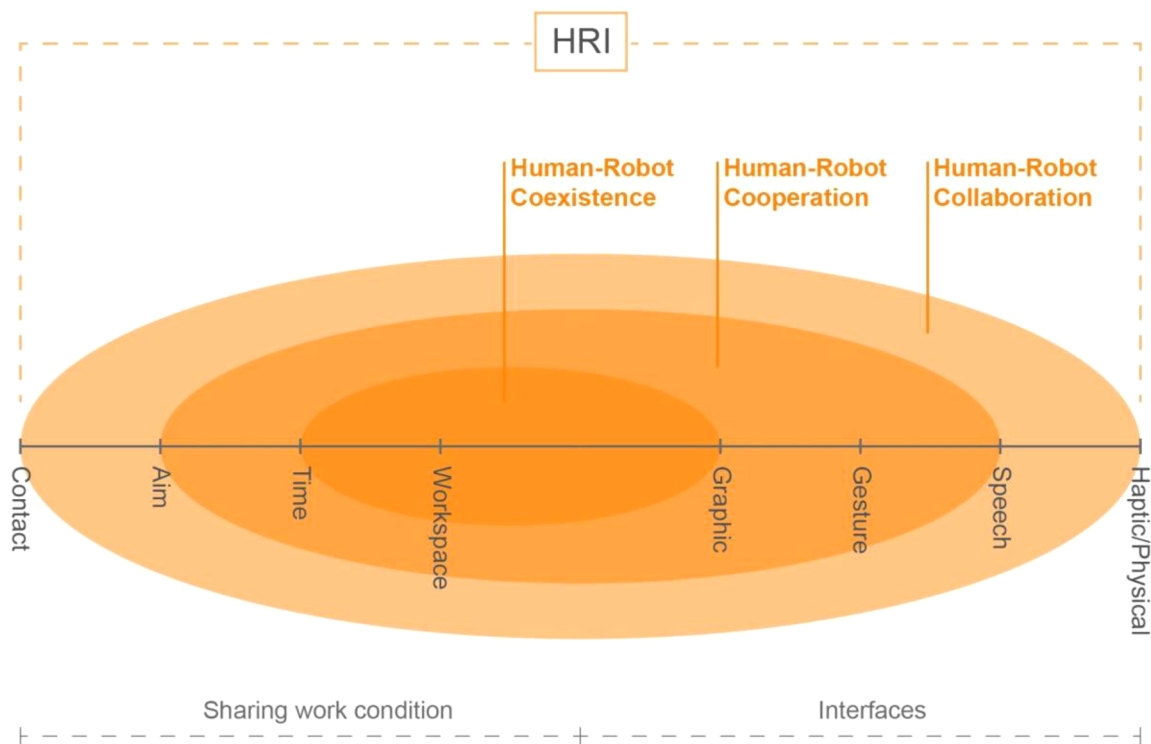


Fig. 1. Framework to classify Human-Robot Interaction: levels of interaction and relations to different interface types

classified into four main categories [18]:

- Visual displays (e.g. graphical user interfaces, augmented reality interfaces);
- Gestures (e.g. hand and facial movements);
- Speech and natural language (e.g. auditory speech and text-based responses);
- Physical and haptics interactions.

Such interfaces can be also related to the level of interaction provided. In particular, the first level of interaction (coexistence) can be usually satisfied by graphical interfaces. The second level of interaction (cooperation) usually requires more advanced interfaces, such as speech and gesture interfaces. Finally, the third level of interaction (collaboration) can require also a direct physical or haptic interaction in order to be effective and natural at the same time. Fig. 1 shows the framework to classify Human-Robot Interaction, considering the three levels of interaction and the relations to different interface types.

As far as interfaces is concerned, the industrial sector is actually more inclined to use visual interfaces. This is probably due to the multiplicity of information options provided to the robot and, consequently, the variety of feedbacks received from the robot. Moreover, they simply offer a clear and unequivocal representation of the work status to the operator. Natural language interfaces have been poorly investigated in industrial context, while they have been already applied for interaction with social robots, such as facial expressions, gaze tracking, proxemics and kinesics, haptic [8]. In some cases, a multi-modal interface may be useful. For example, a natural interface can be used for simpler or more frequent communications, while a visual interface is reserved for complex and less frequent information exchange. Moreover, interfaces should be intuitive so as not to hinder the human work. This means that the interface must be highly usable even by novices and people without a particular knowledge on the use of the technology. For this purpose, human-robot interfaces should allow easy situation control, intuitive giving commands, and clear understanding of feedback sent by robots.

## 2.2. Human Factors for the study of HRI

From the analysis of the literature review, the research about industrial HRI and HRC poorly includes a human-centred approach so far. It can be stated that human factors have been included mainly by focusing on safety, such as the lightening the burden of work. For this reason, the majority of the researchers focused on developing technologies that allow a side by side interaction between robots and humans, to facilitate their work, without a real, close collaboration between them. A specific line of research about interface is directed towards gesture recognition [19] and gesture data set identification [20] for human-robot communication. Another recent line of research is about affective robotics to study the adaptation of robot behavior according to the operator's cognitive workload, detected by monitoring the human physiological parameters (e.g. electrodermal activity, eye gaze, facial expression) [21,22]. For instance, [23] proposes to recognize the user's heart rate (index of stress, anxiety or fear) using a smartwatch and consequently to adapt the level of robot's autonomy. In addition, Virtual Reality (VR) technology can be used to simulate the HRI scenario during the design phase thanks to the development of a digital twin. Recent studies propose to use VR to verify the effectiveness of the human-robot collaboration [24] or to perform virtual user testing, avoiding dangerous situations [25].

Actually, collaborative robots that work alongside humans without a fence must respect the ISO safety standards [13,17,26]: these standards establish a set of precise rules about the robot behavior, like the reduction of the speed and the power, based on the distance of the operator from the robot. Based on these standards, collaborative robots are classified into: Safety Monitored Stop (SMS), Hand Guiding (HG), Speed and Separation, Monitoring (SSM), Power and Force Limiting (PFL) [27]. However, such standards do not focus on interfaces, that are the item that allows the communication and the development of a common understanding between humans and robots.

As far as interfaces, adopting a Human Factor perspective is necessary to design the most proper communication strategies in order to allow an intuitive and effective cooperation and collaboration between

humans and robots. Authors suggest to apply three different views in industrial HRI, similarly to the model proposed in social robots field [28], in particular:

- Robot-centred view,
- Robot cognition-centred view,
- Human-centred view.

Merging the human-centred view with the traditional robot-centred views means including human factors and main principles from Human-Computer Interactions (HCI) and Human-Machine Interaction (HMI) to this specific context, as traditionally human-centred disciplines. Indeed, HRC research cannot focus on technological development without investigating if the result will be good for the human interaction. As stated by the International Ergonomics Associations (IEA), human factors “encompasses not only physical safety and health, but also the cognitive and psychosocial aspects of living and working” [3]. As a consequence, strengthening the inclusion of human factors in HRI should allow reducing both physical fatigue and cognitive effort. In fact, cognitive factors, including topics such as communication and perception, can greatly benefit HRI in general, and manufacturing applications in particular [29]. A key aspect for successful HRI is focusing on the User eXperience (UX), defined by ISO as “a person's perceptions and responses that result from the use or anticipated use of a product, system or service” [30]. In this context, research on social robots has recently recognized the role of UX design to ensure a positive interaction. Indeed, a negative experience could prevent taking advantage from the robots' features or worse from refusing interaction with them [31]. Only the accurate study of UX from the early design stage can ensure an acceptable and pleasant human-robot interaction, able to improve also efficiency and effectiveness of interaction. An example of social features applied to industrial robots is Baxter by Rethink Robotics. It has a screen on which “his eyes” are displayed and these give humans the impression of being able to create eye contact with the robot and to create a natural communication channel.

About the inclusion of UX in robotics, four trends about the UX consideration during the design of socially interactive robots (from level 1 with high consideration, to level 4 low consideration have been pointed out [32]. Up to now, the UX consideration level in the industrial robot design may be placed at the third level, due to the frequent omission of UX aspects in favour of robot-related aspects. However, considering the way the operator interacts with the robot and understanding his/her UX is hard, especially in the industrial sector [8]. In order to overcome this issue, a structured human-centred approach has to be adopted to support designers to solve the technical questions looking at the user's needs and abilities, using UX-based techniques.

According to UX principles, the quality of interaction can be measured by mainly evaluating the use of interfaces and the input/output information exchange between the human user, the interface, and the robot. One of the most common tools in UX is usability assessment, widely adopted to assess the quality of interaction with any interactive systems. It considers three indicators (i.e., effectiveness, efficiency and satisfaction) and proper metrics (e.g., execution time, errors, information request) to measure the user performance [32]. However, there are no specific standard techniques for assessing the human-robot interaction [33], even though they are strongly expected in many studies [34].

In this context, an in-depth picture of interface evaluation methods is provided by [35]. In HRI evaluation, two types of methodologies can be defined: the first type of methods looks more at the robot performance and behavior, while the second type on the user's feels. User testing should be performed under the actual conditions of use, therefore involving end-users, performing real tasks in the real use scenario. In case of tests on prototypes, it is recommended to recreate the operative context as likely as possible: conditions have to be replicated as much as possible, only the type of data to collect will change. Some

examples can be found in the recent literature. An interesting approach has been presented by Steinfeld et al. [33] that assess HRI considering human and robot as a team and studying how they effectively accomplish a task. They consider also the system in its complexity, not only humans and robots, and anything that can affect the task performance (e.g. communication delay, robot update rate, human personnel factors). Diversely, Olsen et al. [36] addressed HRI considering the autonomy of the robot to understand how much the user attention is required. Moreover, Crandall et al. [35] try to understand how many robots the operator can manage.

Other set of evaluation techniques investigates more closely the user's behavior and perception. According to Lindblom and Andreasson [31], useful evaluation techniques could derive from HCI field and could be adapted to HRI. For example, usability tests can be mainly divided into quantitative and qualitative. Quantitative tests do not give indications on how to solve usability problems but carry out measurements (e.g. execution time, number of errors, number of tasks completed) therefore allow to collect data. These data can be collected during the observation of users while performing a specific task. These tests can be more useful for example to compare two types of interface. Quantitative methods also include questionnaires. The questionnaires are useful for gathering a large number of opinions in a short time, as well as being adaptable to multiple application areas. More specifically, Bartneck et al. developed five questionnaires to measure the users' perception of social robots [34]. Among these, the “Perceived safety” questionnaire could also be taken as a reference in the manufacturing sector.

In addition, physiological measurements represent another group of objective measurement tool. These techniques allow to investigate in real time the level of cognitive load and stress of the operator during the interaction. Among quantitative techniques, there is the monitoring of human parameters, such as the measurement of the heart rate (HV), the breathing rate (RBR) or pupil dilation (PD). Examples of adoption of these tools in manufacturing is provided by [37]. A different approach is used in qualitative tests, which aim to collect useful insights to improve interaction, using user observation or interview. In this way, the expert can collect data about the interaction modalities, user experience, and his/her perception and feelings. Qualitative tests are usually performed on fewer participants, since they require more time and more active user participation.

From the analysis of the existing literature, researchers seem to be aware that the introduction of robots significantly affect the human work. However, the approach to HRI design does not seem to take it into consideration yet. Especially in the manufacturing sector, the introduction of robots into industries is not just a replacement of previous machinery. Moreover, the introduction of robots introduces a substantial change in human behaviors. For this reason, there is the need to develop a structured methodology that allows to face a HRI project starting from the analysis of human needs and requirements, according to a human-centred approach. It means designing having clear from the beginning the operator's needs in terms of communication and information exchange with the robot. Only in this way, also complex industrial projects can succeed, achieving all the potential benefits.

### 3. The research methodology

#### 3.1. The UX-based approach

The proposed approach is aimed at introducing a set of UX techniques to support the design of human-robot interface to build up HRI-HRC applications. Indeed, UX is often taken for granted but, contrarily, a positive UX has to be systematically designed [29]. According to the human-centered approach, end-users should be involved in the whole design process, from the first research stage until the final evaluation.

The first step to proceed with a UX approach is the creation of a multidisciplinary team. Such a method can guarantee a proper

information sharing and combination of knowledge from different disciplines in order to detail the usage scenario and have a clear view on the final result. Specifically, teamwork allows an easier identification of the human-robot information exchange in terms of: information typology, physical location, frequency and temporal location, and environment of interaction. Besides, it would provide a shared methodology for the analysis of all case studies.

After that, the user is put on the center of the design process during the so-called “user understanding” phase [38]. It consists of a deep, accurate user analysis based on context research and user analysis, to be carried out in a more or less invasive way. The main UX techniques adopted for user understanding are: user observation, focus group and interview [39]. User observations is frequently used for the context analysis and preliminary user analysis, since it allows to observe user in their natural environment without affecting their normal behaviours and performance. Diversely, focus groups and interviews provide a more active participation of the user to collect, in different ways, qualitative data about user needs, expectations or fears. Usually personas and usage scenarios are defined to represent the results of the analysis.

In addition, different kinds of mapping tools can be used in UX design to describe various aspects of interaction and processes associated. In particular, task analysis allows to define the steps that the user must take in order to complete a goal. In case of collaborative tasks, it can depict the actions taken by the different users (or some systems/robots) to help them achieve their goals. It is useful to have a unique overview of the process activities and to review the all process, minimizing the number of actions that a user has to undertake, analyzing the information exchange or eliminating unnecessary steps. Also, link analysis can be useful to evaluate relationships and connections between users and systems efficiently in a graphical way. Link analysis has been used for user investigation in different field, from criminal activity to [computer security analysis](#), until market research [40]. Moreover, other techniques can be adopted to graphically represent the results of the user analysis [39]. Hereafter some examples are provided [41]. Empathy maps show the user's perspective regarding the tasks and are frequently used to articulate the knowledge about a particular type of user, helping the design team to understand the user's mindset. They graphically externalize the user knowledge in order to create a shared understanding and to support decision-making. Journey maps focus on a specific customer's interaction with a product or service, visualizing the process that a user goes through in order to accomplish a task. They are generally used for understanding and addressing customer/user needs and pain points. Finally, service blueprints are counterparts to customer journey maps, focused on the employees. They visualize the relationships between different service or process components (including people, machines, any physical or digital evidence), reflecting on the organization's perspective with a particular focus on the service provider and employees. The UX-based workflow is schematized in [Fig. 2](#).

When the design is completed, users are involved in the project evaluation phase to test the real efficiency, effectiveness and satisfaction during the use of the final design. In this phase, the involvement of end-users can highlight if there are aspects that had not been considered by the design team. A powerful mean for solution prototype and user testing is represented by the use of Virtual Reality (VR) simulations. Indeed, VR environments enable to directly involve users in task simulation and test the UX about layout, coordination of activities, and interactions with robots or other actors involved.

This research focuses on industrial applications, with particular attention for the manufacturing sector. In this sector, the potential use cases are almost unlimited thanks to the extreme adaptability of robots and the large number of applications that can include both humans and robot, collaborating and cooperating. For this reason, the proposed approach is general-purposes and largely adaptable to different cases. Each use case will than adapt the proposed method to its specific

particularities and scopes.

### 3.2. The UX-based specific tools

According to the proposed approach, the research selected a set of UX specific tools to support the human-robot interface design. The adopted tools are as follows:

- User analysis (observation, focus groups, interview);
- Task analysis;
- User/Task Matrix (new tool);
- Experience Maps (new tool).

These tools allow to carry about a robust, human-centred user requirement analysis, that is the main issue to guarantee a good UX design. After that, the design phase will define the main features of both robots and workplace. The use of prototypes is useful to check if the solution identified is the right one. Also in this phase, it is possible to involve users to collect their opinions and first impressions. This will make it easier to solve some problems encountered.

A HRI design flow has been defined according to a UX-based workflow. It is made up of 4 steps as follows:

1. Requirement gathering:
  - 1.1 Creation of a multidisciplinary team (e.g. involving system engineers, IT engineers, User Interface and UX designers, system developers, system integrators);
  - 1.2 User analysis (using observations, focus groups and interviews);
  - 1.3 Activity analysis (using task analysis);
  - 1.4 Interaction visualization (using User/Task Matrix and Experience Maps);
2. Interface Design;
3. Prototyping;
4. UX assessment (based on user testing).

Like all design cycles, the process may be nonlinear but rather iterative, requiring many cycles through the process.

The main novelty is the introduction of typical UX-based tools in the requirement gathering phase, to focus on human factors. In particular, interaction analysis and visualization represent the key-points of the entire process. Experience maps generalize the concept of customer-journey maps across different user types and products. They represent a synthetic visualization of an entire end-to-end experience that a “generic” user goes through in order to accomplish a certain goal. They are used for understanding a general human behavior, as opposed to journey maps that are more specific and focused on related to a specific business. This tool is better presented hereafter.

The User/Task Matrix is used to synthesize all information about users and tasks, and operational conditions into a table. An example of its structured is shown in [Fig. 3](#). The matrix organization, indeed, allows to collect a set of information and data into a structured way, to clearly describe the process interaction and to easily compare different scenarios. In particular, the Matrix contains all the necessary data to guide the choice of the interface type, which is largely influenced by multiple aspects [42]. First of all, the Matrix considers the tasks to be performed, their temporal sequence and the temporal relations among different activities. Secondly, it maps who performs the different actions (e.g., operator, robots). Thirdly, it describes the specific working conditions, such as environmental conditions (e.g., noisy, small, dusty) or the use of personal equipment (e.g., gloves, goggles, helmet). This information is useful to guide the choice of the most proper interface, excluding or preferring some types of interfaces to others. Once these factors have been clarified, information about the actors involved are collected. Finally, also the situations in which errors occur and how to solve them can be useful to design the interface. For example, under normal conditions, human-robot communications could be limited to

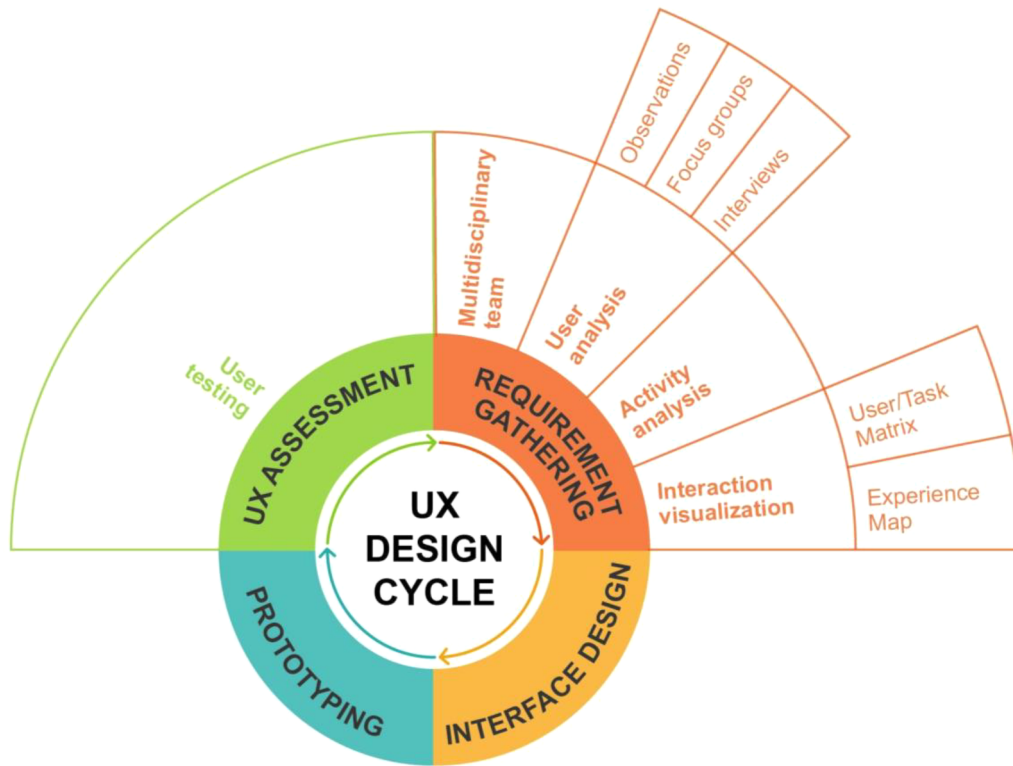


Fig. 2. The UX design workflow as proposed for HRI

simple feedback through the use of lights, but in case of problematic situations, the user may have to view the data, therefore a graphical interface would be more suitable. Such a model considers the interactions in term of information exchange from the user perspective, like commands given by the user or feedback received from the robot. It does not take into account physical interactions (e.g. hand-guiding) or

emotional aspects.

Fig. 3 shows the template for the User/Task Matrix proposed in this study. On the rows, the tasks are listed, directly taken from the task analysis. On the columns, the Matrix considers the following items:

- Tasks (e.g., cycle tasks, monitoring/control tasks, and any activity

Tasks		Actors	Duration										Communications			
Tasks	Monitoring and control task		1	2	3	4	5	6	7	8	9	10	...	Operator to Robot (input)	Robot to operator (Feedback)	Operator to operator

Difficulties and critical situations	Solutions and intervention by the operator	Working conditions						
		Workspace			Operator			
		Noisy space	Restricted handling space	Presence of dust	Gloves	Glasses	Elment	Other

Fig. 3. Template for User/Task Matrix to study HRI as proposed in the research



- carried out from operator/s or robot/s);
- Actors (e.g., operator/s, robot/s)
- Communication between the actors involved (e.g., operator to robot, robot to operator, operator to operator);
- Cycle time (expressed in seconds);
- Critical situations and possible solutions (e.g., difficulties or trouble situations, possible solutions and interventions by the operator);
- Working conditions (e.g., related to the environment and related to the operator/s).

The User/Task Matrix synthetically describes the interaction and supports designers in the definition of the most proper interfaces. This tool should be dynamic: it should be compiled by the multidisciplinary team at the beginning of the design process, and regularly updated as the project continues, with an increasing level of detail as soon as the interaction scenario becomes more defined.

In order to fill in the matrix correctly, some recommendations are proposed to stimulate a proper reflection on the above-mentioned items:

- **Tasks and Duration:** it provides a list of the tasks, differentiating between cycle or monitoring/control activities, and the chronological order of each of them;
- **Actors:** it associates each task to the actor/s performing the specific action;
- **Communications:** it refers to the individual tasks, think about the specific type of input or feedback that the operator should give to the robot or vice versa, in different moments (before, during and after task execution). Some guiding questions:
  - What information or command must the operator provide to the robot?
  - What information and feedback must the robot provide to the operator (e.g. completion of activities)?
  - Can fast commands be useful for the operator to dialogue with the robot / s (e.g. stop, slow down)?
  - What inputs might the operator need to provide in case of error / problem?
- **Cycle time:** it indicates the duration of each task (e.g., in seconds) and reports at least 2 activity cycles to understand the succession of production cycles.
- **Critical situations and possible solutions:** for each activity, it provides a list of possible difficulties and predicts the critical situations that could arise (e.g., lack of material, difficulty of the operator in carrying out his task, low control on the process). Some guiding questions:
  - Does the operator encounter difficulties in carrying out his tasks? What are his/her needs?
  - What critical situations could arise?
  - How should the operator intervene to solve the problem? What does he/she need (e.g. instructions, data, specific information)?
- **Working conditions:** for each task, it indicates the specific environmental conditions (e.g., if the environment is noisy, restricted or with dust) and indicate whether the operator wears personal protective equipment (e.g., gloves, helmet, glasses).

#### 4. Experimental validation on industrial cases

A set of industrial use cases have been identified to validate the proposed method. They have been developed within an Italian Research project in the field of Smart Factories. In particular, the paper describes the experimental results obtained on one use case, focusing on the assembly of two counter-rotating shafts by a collaborative robot and an oil pump on a crankcase by a human operator, both supported by two AGVs (Automated Guided Vehicles). Such use case is quite complex since it involves different actors (e.g., human operator, collaborative robots and AGVs). Each actor has a specific role and must be

coordinated with the others. In fact, both human-robot and robot-robot collaboration take place. Furthermore, the use case is a valuable example of how the human-robot communication is fundamental for a broad reasoning on interface design.

##### 4.1. Use case analysis

The use case described in the paper considers five different actors:

- 1 human operator;
- 2 collaborative robots, in particular anthropomorphic robots (respectively a KUKA robot and a FRANKA robot);
- 2 AGV lines (each line is considered as an actor).

More specifically, AGVs operate on two lines: the Kit Line and the Motor Line. On the Kit Line the AGVs move on-bound and transport the assembly components (i.e., counter-rotating shafts, oil pump, and necessary small parts). These AGVs make two stops (firstly on position A and secondly on position C) to allow the picking of the components. Each AGV working on this line is defined as Kit AGV. On the Motor Line, the AGVs carry the crankcase and move in the opposite direction. These AGVs make two stops (firstly on position C and secondly on position A) to allow the placing of the components. The human operator stays on position A and performs the double task of inspecting the kit transported by the AGVs, and then picking up and positioning the oil pump on the crankcase (positioned on an AGV of the motor line). Each AGV working on this line is defined as Motor AGV.

One of the two collaborative robots (R1) moves on a linear rail (from position C to position B) for continuously assembling the two counter-rotating shafts (one for discharge and another for suction) on the crankcase (positioned on an AGV of the Motor Line). Instead, the second robot (R2) remains fixed in position C to pick the two counter-rotating shafts from the AGV on the Kit Line and pass them to robot R1. Fig. 4 shows the use case actors and work cell layout.

Task Analysis allowed to study the process activities and to analyze the interactions on the three positions (A, B and C). A consequence, operations can be described also with respect to the place where they take place (A, B and C) as follows:

- **Position A:**
  - Kit AGV operating on the Kit Line stops (first stop);
  - Motor AGV stops (second stop);
  - Operator checks the assembly components, picks up the oil pump and positions it properly on the crankcase, located on the Motor AGV;
- **Position B:**
  - Robot R1 completes the placing of the second counter-rotating shaft while it's moving in parallel with the Motor AGV;

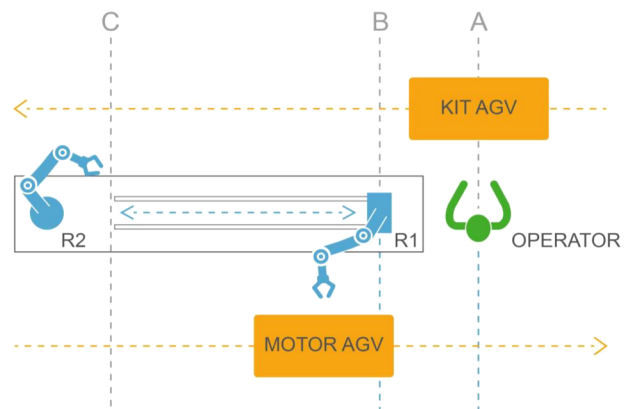


Fig. 4. The use case actors and work cell layout

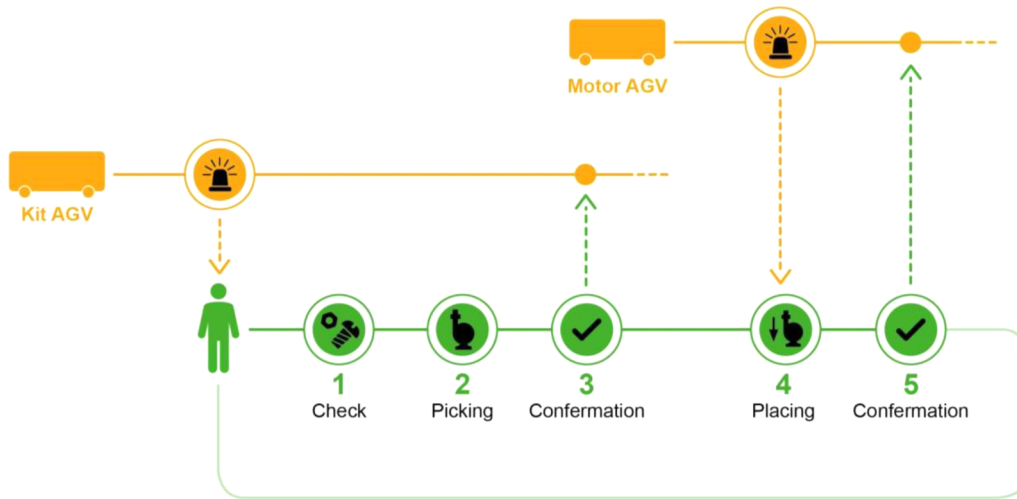


Fig. 5. Experience map for the use case - regular conditions

- Position C:
  - Kit AGV stops (second stop);
  - Robot R2 picks the two counter-rotating shafts up and passes them to Robot R1;
  - Motor AGV stops (first stop);
  - Robot R1 places the first counter-rotating shaft of the crankcase, located on the Motor AGV.

#### 4.2. Results and discussion

As a result of the UX-based analysis, the User/Task Matrix was completed and the Experience Map was defined to fully describe the interaction.

About the User/Task Matrix, all tasks performed in the cycle were related to the actors (i.e., operator, Robot R1, Robot R2, Kit AGV, Motor AGV) and were reported in a temporal sequence. Such preliminary analysis was initially useful to clearly recognize that some tasks occur simultaneously and to understand with actors are involved in each specific task. Moreover, all the information related to the interaction modalities, communication needs, and working conditions were collected and formalized. The main tasks analyzed are listed below, indicating the position where they take place:

- Kit AGV: Move to the first stop (A);
- Operator: Control of the two counter-rotating shafts, the oil pump and the assembly components (A);
- Operator: Pick-up the screws and the oil pump (A)
- Kit AGV: Move to pick-up location (C)
- Robot R2: Pick-up the first counter-rotating shaft from Kit AGV and positioning in exchange area for transfer with Robot R1 (C)
- Motor AGV: Move to the first stop (C)
- Robot R1: Move to the exchange area for picking up the first counter-rotating shaft from Robot R2;
- Robot R1: Insert of the first counter-rotating shaft on the crankcase;
- Robot R2: Move back and pick up the second counter-rotating shaft (C);
- Robot R1: Move to exchange area and pick up the second counter-rotating shaft from Robot R2 (C);
- Robot R2: Return back (C);
- Motor AGV: Move to position B;
- Robot R1: Insert the second counter-rotating shaft on the crankcase in continuous moving up (B);
- Motor AGV: Move to the next stop (A);

- Operator: Mount screws and oil pump on the crankcase (A).

The complete analysis carried out for the use case is described in the compiled User/Task Matrix reported in [Appendix A](#).

From the analysis of the User/Task Matrix, a lot of useful information about the number of tasks, their type and duration, and the communication needs can be retrieved into a unique, overall view. In particular, it helps to understand how complex the global activity is. The execution of multiple tasks simultaneously provides an image of the movement of the actors involved and therefore also gives an idea of the presence of noise or total confusion. These, for example, can make the operator feel stressed or uncomfortable in this context. The list of information necessary for both the operator and the robot allows to understand the frequency of human-robot interactions, how complex they are and how long they take. It is possible to better understand how much the interactions affect the execution of the activity. In addition, such a matrix allows to easily look beyond the mere data and provide a more in-depth view reading the global interaction scenario, especially about how the operator will feel inside it.

Finally, the Experience Map was defined after a carefully study of the process, on the basis of the User/Task Matrix, and by focus groups. Indeed, if the User/Task Matrix describes the entire process, the Experience Map focuses on the human operator experience and map his/her "journey" along the process. This tool refers to the experience of interaction between the user and the surrounding environment, and it is strictly linked to the performed activities. In this context emotions and subjected feelings are not included. The set of activities and interactions certainly are affected by emotions, which however are difficult to predict at an early stage of the project. Emotions also depend on the specific users that are unknown at this stage. The Experience Map, however, is also suitable for adding references to the user's mood at a later date.

For the specific use case, the global UX can be summed up into five steps on regular conditions, as indicated in [Fig. 5](#). It sums up the tasks that the operator has to accomplish (on the green line) and the main interaction points with robots and AGVs (on the orange line). Moreover, [Fig. 6](#) and [Fig. 7](#) provide the UX maps in case of robot error and AGV error respectively.

From the UX analysis, the interaction types and communication needs can be easily detected and studied. For instance, the maps highlighted that in regular conditions the operator only interacts with the two AGVs and not with the collaborative robots. But it does not mean that attention should be paid only on communication with AGVs. Indeed, the operator has to have also a complete control of the overall process and to take care also of the tasks carried out from the two

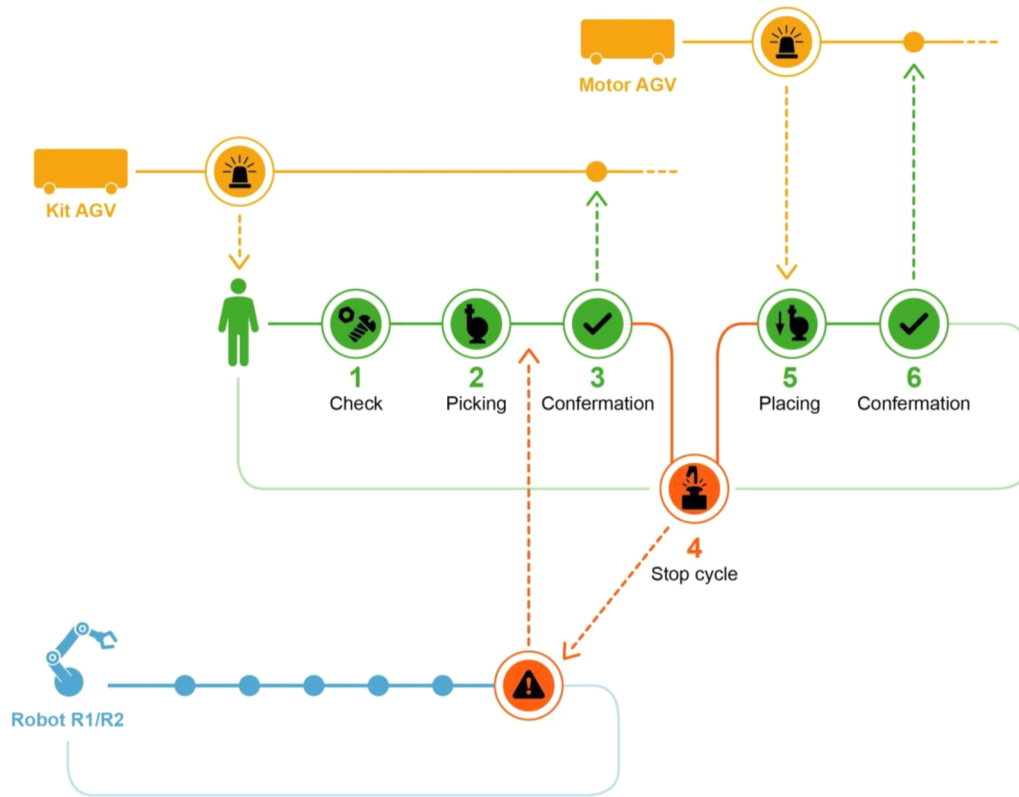


Fig. 6. Experience map for the use case - robot error

collaborative robots. Instead, the map elicits the two different types of interaction in the two cases: with AGVs interaction is mostly related to start/stop commands and controlling their proper positioning; while with collaborative robots the operator needs to have a timely feedback on their status and progress of the different activities. Furthermore, the maps helped the understanding of interaction also when errors could occur, to finally identify the user's needs and interaction requirements.

The application of the proposed UX-based tools to the specific use case also supported the validation of the method for the definition of

interface design guidelines. In particular, a first analysis of the User/Task Matrix was useful to create a general situation awareness of what happens within the workstation. After that, a more careful analysis was necessary to better understand the most proper type of interface in relation to the specific interaction issues, interface features and positioning in the workplace, and finally the preferred access modality considering also the most suitable device. This second analysis considered firstly generic information and secondly more detailed data. For instance, it started from the analysis of the Working conditions

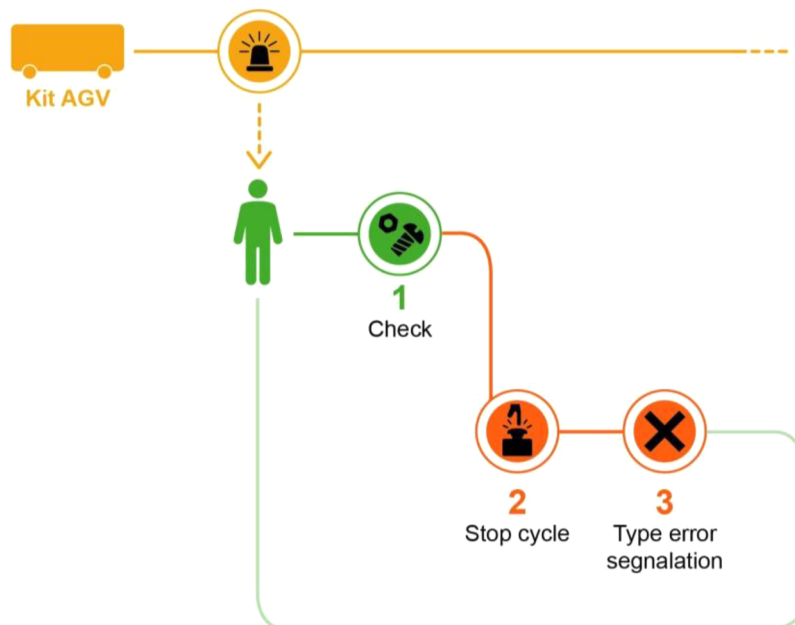


Fig. 7. Experience map for the use case - AGV error

(referring to firstly the operator and then the workspace). This column gave indications on which types of interfaces should be adopted in the specific context of use. In the use case, there were no particular working conditions to exclude some interface types (e.g., gesture, speech), but observing the operator conditions (i.e., wearing gloves) suggested to exclude touch interfaces specifically. However, visual interfaces could be adopted but input devices were carefully chosen. The second aspect to consider is Communications. This column provided useful indications about the direction of communication (i.e., from operator to robot, from robot to operator, both), the moment of communication, the frequency of information exchange, and the information complexity. More specifically, the level of complexity was determined by the combination of the level of detail required and the variety of communications. On one hand, if communications are simple (e.g., stop, slow down), natural interfaces can be successfully implemented by gesture or speech interfaces. However, if messages to be shared are simple but also frequent and numerous, the operator could difficulty memorize them. On the other hand, if communications are complex and based on long sequences, natural interfaces are not suitable since they poorly support message composition and decoding, and do not guide the user in the correct interpretation. Considering the complexity of the contents to be transmitted, also data indicated on the columns about critical situations and solutions were used. Indeed, interface dialogue must be particularly effective in critical situations. In those cases, where standard communications and critical situation communications have a very different level of complexity, it may be useful to provide two different types of interfaces: the former for regular communications (frequently accessed), and the latter for problematic situations (poorly accessed).

Observing the task timeline also supported understanding when the communications took place and in what conditions the operator provided inputs or received feedbacks. Time analysis as well as communication frequency analysis helped to define also the type of use (e.g., co-located, remote, ubiquitous), the size of the interface, and their most proper positioning. In case of very frequent communications, handheld interfaces should be preferred to guarantee an easy and ubiquitous access whatever the user position.

Looking at the information collected of the use case, it was possible to define the following design guidelines for interface design:

- the workplace conditions allowed the use of theoretically any type of interfaces;
- in case of using visual interfaces, the operator conditions suggested to adopt physical devices (e.g., buttons, mouse, knobs) or touch screens able to recognize the touch with gloves (e.g., projected capacitive touch screens);
- communications was bidirectional, from operator to robot and vice versa, and was characterized by medium-frequent exchange and low complexity, so that ubiquitous and/or wearable interfaces could be considered. Moreover, multiple interfaces could be used to received different kinds of feedback: for example, a light switch, a short sound, a vibration of a wearable device or a visual pop-up on the screen could be used to provide different types of information, simplifying the comprehension process on the user mind. At the same time, the operator could inform the systems about his/her activity by a speech interface (e.g., using the keyword "Go!"), hand gestures (e.g., open hand or fist);
- communications did not overlap with other activities, therefore the operator could devote attention to both receiving communications from the robot and sending commands;
- communications during critical situations were characterized by a higher level of complexity, but a lower frequency. For these purposes, physical or digital commands / buttons could be used. For example, stopping the entire cycle could be carried out by simply

pushing a physical or digital button, clearly dedicated to extraordinary situations (e.g., red color and more distant position from those used for other activities). Similarly, in case of incorrect or absent kit components, the operator should communicate the specific problem by a visual interface, that is the easier way to refer a problem and call for assistance.

Such analysis provides an example of how the combination of all information retrieved from the UX tools can practically guide the interfaces design. The proposed analysis supported the definition of the interface and the main design issues, but also prototype assessment using the User/Task Matrix to verify the satisfaction of the user requirements, and the Experience Map to validate the effective UX on the prototype.

This method requires a good sensitivity of the design team and a good level of expertise to interpret the collected data and relate them in order to obtain useful information for the design. Moreover, time spent to analyze interactions is then saved during the design phase and leads to better results as well as preventing problems in the more advanced design phases.

Finally, both the User/Task Matrix and the Experience Map can be customized and expanded according to the specific needs of the project.

## 5. Conclusions

The paper deals with the design of interface in Human-Robot Collaboration (HRC), when modern robots collaboratively execute tasks supporting humans within the modern factories. The research motivation arises from the need of extending the current research, mainly focusing on technological aspects on the robotic side, towards the human side. In particular, this work proposed a UX design cycle as a methodology to include human factors in human-robot interface design, with the final aim to elicit the needs of human beings interacting with robots. The paper provided also a set of UX-based tools to investigate the human-robot dialogue, to map the UX and the interaction with robots during the execution of shared tasks, and to finally elicit the design requirements for designing usable and effective interfaces. The research validated the application of the proposed tools on an industrial case focusing on assembly operations, where humans collaborate with anthropomorphic robots and AGVs (Automated Guided Vehicles). A multidisciplinary design team was created to map the interaction and define the design requirements using User/Task Matrix and Experience Maps. The novelty of the proposed approach is the inclusion of UX-based design tools in HRC design. Results demonstrated the validity of the proposed tools to understand the human-robot interaction, describe the communication issues, and define the main interface features to support the following interface design activity.

### Disclosure statement

No potential conflict of interest was reported by the authors.

### Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

Figs. 8-9.

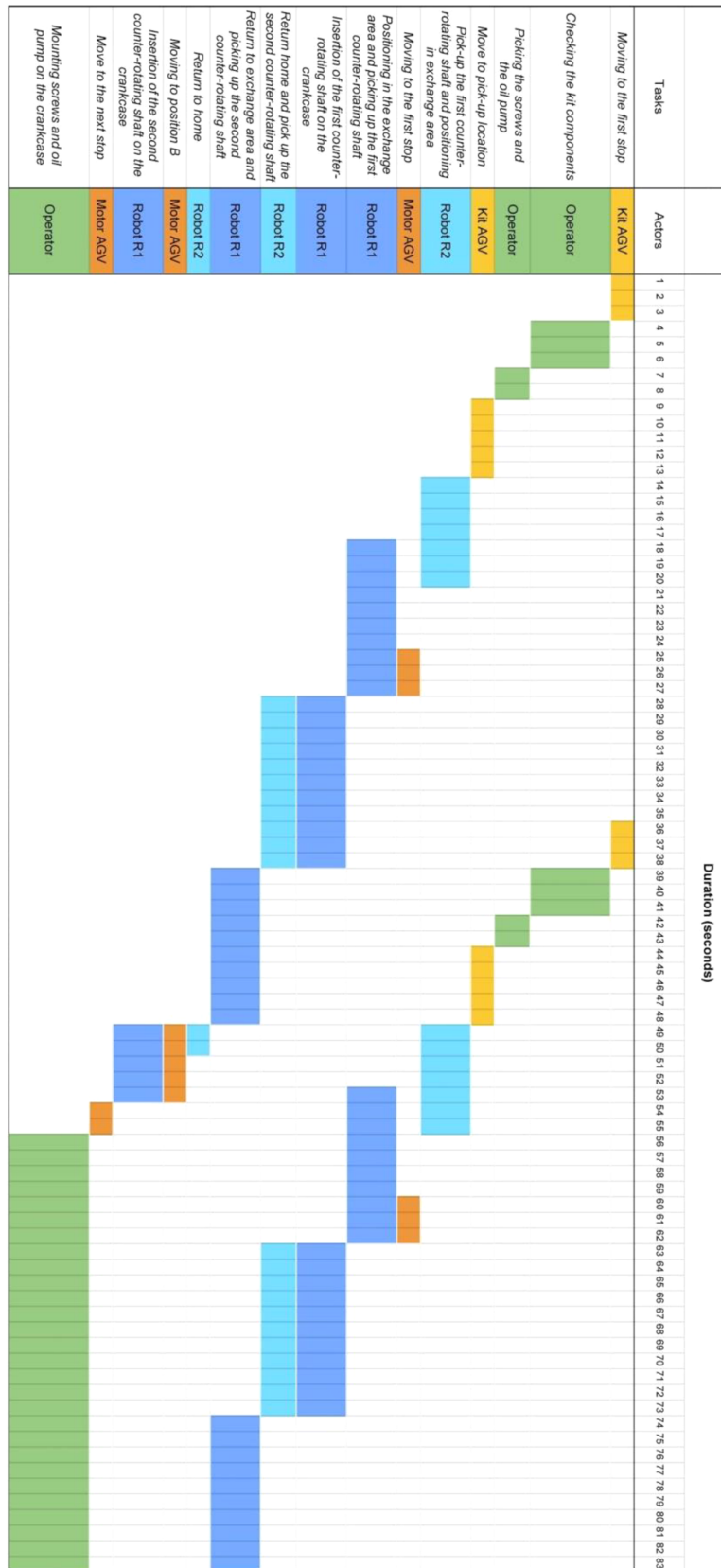


Fig. 8. User/Task Matrix for the use case - part 1



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