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Use of interaction design methodologies for human-robot collaboration in industrial scenarios

Elisa Prati[1], Valeria Villani[2], Fabio Grandi[1], Margherita Peruzzini[1], Lorenzo Sabattini[2]

***Abstract*—In this paper we address the problem of designing a collaborative robotic system for industrial applications, focusing on the characteristics of the interaction. The key concept of collaborative robotics is that of allowing a strict interaction between the human user and the robot itself: hence, the study of the interaction is of paramount importance for a successful implementation of the system. While safety and adaptability of the robotic systems have been widely studied in the literature, little attention has been devoted to the definition of the interaction experience. This paper aims at filling this gap, proposing the use of interaction design principles to the definition of a collaborative robotic system.**

***Note to Practitioners*— This paper aims at bridging the gap between interaction design and collaborative robotics. It will provide tools for robotics experts (researchers and system integrators) for understanding the user experience, and design the robotic system ensuring an effective interaction. Such principles are commonly adopted in the design of computer-based human-machine interfaces or web applications, but, to the best of the author's knowledge, have never been applied to the design of collaborative robotic systems for industrial applications.**

***Index Terms*—User interface human factors, user centered design, collaborative robotics, interaction design.**

I. INTRODUCTION

In the last years demand for robots in industries has risen considerably due to the ongoing trend toward automation and continued technical innovations in robotics [1]. On the one side, progresses have been made with respect to traditional industrial robots in terms of safety, with sophisticated and versatile sensors, and improved performances. Moreover, on the other side, the introduction of collaborative industrial robots has promoted a novel use of robots, no more seen as naive tools, but rather flexible collaborators. Flexibility, scalability, and lower cost of entry than traditional robots have allowed small- and medium-sized enterprises to benefit from collaborative robotics without the often cost-prohibitive up-front expenses of traditional industrial robots. Solutions based on human-robot collaboration (HRC) allow to combine the advantages of automation, such as accuracy and repeatability, with the flexibility and cognitive (and soft) skills of humans [2], [3]. Thus, collaborative robots meet the needs of modern automation for flexible manufacturing of small lot sizes with high quality.

In this scenario, human workers still represent the most valuable asset of every company [4]. They guarantee the high levels of flexibility and cognitive load that are fundamental for modern manufacturing but are currently unattainable by robots [4]. To promote humans' roles, it is then important that the factories of the future adapt their organisation and production systems so workers are valued and get more meaningful and healthy jobs [4], [5].

Moving along these lines, it becomes of paramount importance that the collaboration between robots and humans takes place in a straightforward, and efficient fashion. Usability and intuitiveness of the collaborative solutions need to be considered since the very early phases of design, in order to let human workers be as comfortable as possible when sharing tasks and space with robots. Many tools have been devised in the domain of usability engineering and anthropocentric design to tailor the design of interaction systems around humans. Capital examples in this regard are the principles of interaction design, from Norman's design principles [6], to Nielsen's heuristics [7] and interaction design dimensions [8]. Such principles are valid rules for any project in which a user interacts with an interface, both physical and digital, regardless of the application context. They share the idea that designing interaction systems does not only mean deciding through which interface the user will be able to carry out her/his operations and communicate with the machine, but also designing the overall user experience. While the application of these principles is quite common in several domains of design, there is still lack of their application in robotics. In particular, as regards industrial robotics, intuitive interaction and smooth collaboration between humans and robots have been considered only with respect to single aspects of HRC, as reported below in Sec. II. A holistic approach is lacking, that considers human factors and interaction related aspects across the whole process of design of HRC solutions in shop floors of industries.

The aim of this paper is, hence, to discuss how tools and principles characteristic of interaction design can be applied to robotics, to design successful and efficient collaborative robotic solutions. In particular, we propose the joint adoption of methodological principles typical of interaction design with practical tools that assist designers in the design of user interfaces, from the analysis of user's needs and interaction processes to the creation of prototypes. Thus, we provide both

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theoretical and practical guidelines for the design of interfaces for collaborative robotics. It is noteworthy that the proposed guidelines have general validity: they do not focus on specific industrial applications of HRC neither they are limited to standard graphical user interfaces implemented on panel PCs in shop floors. Rather, the proposed tools and methodologies can be tailored for different applications and interaction means. To show concrete application of the discussed methodologies, we present their application to two industrial case studies:

- **Case study 1** considers the problem of assembling a complex mechanical part. As a representative example (without loss of generality), we will consider the case of assembly of an engine for automotive. Such assembly operation is performed by a human operator, assisted by automated guided vehicles (AGVs) and collaborative robots. While the AGVs solve the task of supplying materials to be assembled and delivering assembled products, the robots are in charge of manipulating some of the parts to perform a portion of the overall assembly task.
- **Case study 2** considers a logistics operation, where multiple AGVs share the environment with human operators. The overall objective is that of collecting components from shelves, to compose an assembly kit.

The paper is organized as follows. In Sec. II we discuss the state-of-the-art of HRC with specific focus on research questions related to interaction. In Sec. III we present the main concept of interaction design, introducing theoretical principles and practical tools, and propose their application to industrial HRC. Examples in this regard are presented in Sec. IV with reference to the case studies presented above. Finally, Sec. V follows with some concluding remarks.

II. BACKGROUND

A. *Background on interaction studies in industrial HRC*

Given the fast growing spread of collaborative robots in industrial workplaces, a large number of research studies have been devoted to improve the usage of such tools, in order to increase aspects related to productivity and enhance collaboration with human operators. In the field of HRC, primary attention has been put on safety issues, which is a clear imperative property that any collaborative scenario must guarantee. Safe operating modes allowing collaboration to different extents have been reviewed, for instance, in [2], [9]. In addition to safety, the need for effortless and intuitive interaction has been considered with specific regard to different aspects of HRC [10]. In particular, in context of HRC in industrial environment, interaction related factors and human factors have been investigated with regards to the following topics: robot programming, task allocation, cell design and physical interaction. Within these domains, approaches have been proposed to provide seamless interaction able to leverage robot and human capabilities.

1) Robot programming: With regard to robot programming, methods have been proposed to avoid the bottleneck of traditional lead-through programming and offline programming. The former consists in teaching the robot trajectories and endpoints by moving it through the required motion cycle using the teach pendant. Trajectories are then recorded into controller memory for later playback. The latter resorts to computer-aided manufacturing for offline simulation of robot program [11]. Although they represent the standard approaches to robot programming currently used in the greatest majority of industrial applications, they suffer from many major drawbacks [2]. The main are that lead-through programming is tedious and time-consuming [12] and is feasible only for simple programming tasks on workpieces with a simple geometry. On the contrary, offline programming is not suited for flexible production and for small batches and, from the point of view of user interaction, it requires advanced programming expertise and, in general, heavy programming effort. Intuitive robot programming has been introduced with walk-through programming and programming by demonstration [2]. The former consists in moving the end-effector of the robot through the desired positions, while the robot controller records the desired trajectory and the corresponding joints coordinates, which can then be played back [13]. Programming by demonstration, which can be seen as an extension of the former, includes the possibility for the robot to generalize the movements performed by the human operator and to repeat them in different conditions in new scenarios. Both these approaches allow to intuitively program robots in a natural and tangible manner, since they avoid the need to translate the trajectories to program in a representation (e.g., code) that the robot can understand. Rather, trajectories are simply shown to the robot freely moving in the space. Furthermore, additional intuitiveness can be achieved by introducing human-friendly interaction modes, such as speech, gesture, eye tracking, facial expression, haptics, in addition to traditional keyboard, mouse, monitor, touchpad and touchscreen [14]–[18]. Such interaction modes help operators to control and program a robot by means of high-level behaviours that abstract from the robot language.

2) Task allocation: Task allocation and planning represent another crucial topic in HRC, since collaboration implies coordination of actions and intentions [19]. Thus, the optimal way has to be found to allocate tasks between the robot and the operator in order to maximize efficiency and throughput in flexible production, possibly considering operator's welfare. In [20] a mixed-integer programming formulation has been proposed for balancing and scheduling of assembly lines with collaborative robots. The model decides on both the assignment of collaborative robots to stations and the distribution of workload to workers and robotic partners, aiming to minimize the cycle time. In [21] the optimal strategy to allocate assembly tasks to humans and robots for coordinated cell manufacturing is based on the calculation of each task's time cost and payment allocation. The specific case of flexible production is considered in [22] and the criteria to select a task allocation plan is the minimization of the expected total production costs. Thus, while common objectives for task allocation are related to production (e.g., minimization of the number of stations, minimization of cycle time, minimization of costs, or maximization of profit) [23], in [24] adaptive task allocation is aimed to relief operators from fatigue and mental stress: the behavior of the robot and the organization of the process are changed depending information about operator's status, the process and context, such as machines productivity and production planning data.

3) Workstation design: As regards cell design, classical studies refer to the use of optimisation techniques for optimising profit and operation time. Nevertheless, human factors are often taken into account, to combine economic and ergonomic factors in the design of workstations. This is the case, for example, of [25], where the design of workstation for collaboration between an industrial robot and an operator is seen as a multi-objective optimisation problem, which analyses both operation time and biomechanical load. In [26] virtual manufacturing has been used to find the optimal layout considering economic and ergonomic goals. In addition to this, in [27] the digital human modelling tool has been included. While the use of virtual manufacturing is a quite established tool for workstation design, the study presented in [28] investigates the effectiveness and acceptability of such a virtual environment for the assessment of HRC in manufacturing. Feedback collected from participants in the study suggestions provides suggestions for improving such virtual environments.

4) Physical interaction: In addition to having the robot and the operator working together at a common goal, the introduction of collaborative robots allows them to share the workspace and, possibly, also work on the same object thus physically interacting. Hence, robotics research has largely focused on the study of safe humanrobot coexistence and dependable interaction [19]. Within this broad research goal, some studies have focused on industrial applications. The case of manual welding with a robot has been considered in [29]–[31]. Therein, the robot is driven by the human welder to guide the behavior of the robot. Moreover, the motion pattern provided to the robot is used to recognize novice and professional welders. Involuntary vibrations typical of novice welders are detected by robot impedance measurements and this information is used to trigger assistance from the robot in favour of less skilled operators. In general terms, most control approaches resort to the measurement of forces and torques exerted by the human during the interaction. These are used to provide inputs to the position control system of the robot by means of compliant control schemes, such as admittance/impedance or force control [32]. In [33] a collaborative human-robot manufacturing cell for assembly tasks has been presented, which manages direct physical contact between robot and human, and between robot and environment. The robot alternates active and passive behaviors during assembly: active behavior is sought to lighten the burden on the operator, whereas, thanks to passive behavior, on-the-fly human intervention can be taken to tackle complex tasks. As another example, safe interaction and contactless collaboration for n industrial polishing task has been proposed in [34]. There, unintended contact or collision with an industrial robot is avoided by modifying online the motion of the robot according to information provided by depth (RGB-D) sensors and laser scanners.

B. Applications of HRC in industries

It is noteworthy that, although many solutions for improving efficiency and flexibility of HRC have been explored in recent years, the solutions that have already been transferred to the industry are quite few. Commonly, collaborative robots are used for performing dull tasks, such as holding or moving heavy objects or repetitive tasks, such as standard pick and place, as if they were cheap industrial robots. Rather than helpful collaborators, in most operative scenarios collaborative robots are still as robot-as-tool [20], [35]. Most of industrial applications of collaborative robots are in the field of automotive [2], [20], since they have been introduced in manufacturing lines by several manufacturers, such as BMV [36], Mercedes-Benz [37], Audi [38], Ford [39] and Volkswagen [40]. Most of these applications refer to assembly task and help workers to perform fatiguing tasks in an ergonomically optimal position (further details can be found in [2]). Other applications of HRC in other industrial sectors can be found for material handling [41], surface polishing [34] and welding [42].

III. PROPOSED APPROACH

A. Interaction design principles for HRCIs

A key aspect in any type of collaboration, and consequently also HRC, is interaction. Interaction strongly depends on the communication flow between the user and the interfaces, and the generated user experience. As a consequence, the design of proper interface is crucial for high-quality HRC, where humans and robots combine their respective skills to carry out a common task in the most efficient and effective way. On one hand, the operator can give to robot inputs in a simple way, without any distraction from her/his main task; on the other hand, the robot has to provide clear feedback, generating an immediate comprehension and data interpretation. Based on this, the design of HRC cannot neglect the basic principles of interaction design.

The design of HRC interfaces (HRCI) for industry requires a structured methodological approach that guides the definition and the design phase of the interactions and interfaces, and at the same time a set of tools to understand interaction and support HRCI design [43]. With the term HRCI we refer to the user interfaces used for collaborating with robots in industrial applications. As pointed out in [2], the greatest majority of such interfaces are visual (e.g., graphical user interfaces on monitors, or physical buttons) and are used for robot programming and managing production processes by setting working parameters (see, e.g., [44], [45]). Nevertheless, other interaction modalities have been introduced recently, mostly based on gestures, speech and physical interaction (e.g., for walk-through programming), as shown in Fig. 1. Thus,

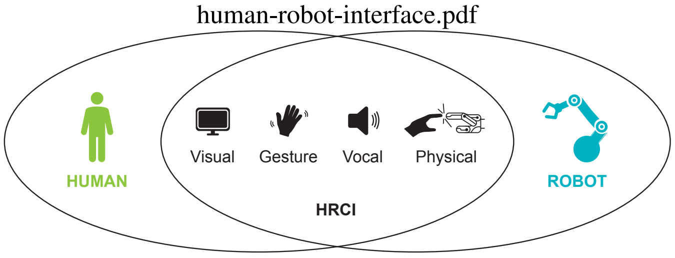


Fig. 1. HRCI concept.

in this paper we aim at providing theoretical guidelines and practical tools to guide the design of these HRCI, whatever the shape they take is. For this purposes, the paper adopts a user-centred approach to design effective HRCIs, based on the main pillars of interaction design, valid to design almost any interactive artifacts between humans and machines.

1) Design principles by Norman: The first step to design interaction is considering the Norman's seven design principles [6], namely: *visibility, feedback, conceptual models, affordance, signifiers, mapping, and constraints.*

In synthesis, these principles state that the interface has to guarantee a good visibility to make the user immediately understand the possible actions and the status of the system. Moreover, the interface has also to provide feedback to make the user understand the system's status and response to her/his actions. The interface should also refer to specific conceptual models about the system organization, with respect to the context of use, to promote user understanding and feeling of control. Affordances are indications, invitations, to possible actions that allow a direct communication between the interface and the user, and are essential to drive the interaction in the right way. Moreover, signifiers are all those elements that indicate where to carry out the actions indicated by the affordances, useful to support the user actions. Mapping refers to the relationship between commands and their respective actions: it makes the interface easy to understand, to learn and to remember. Finally, constraints are useful to prevent certain actions and to avoid errors. These principles normally regulate the interaction between humans and the real world: hence, they apply to robots and must be considered in HRC.

2) Heuristics by Nielsen: Considering more specifically the interface design, more direct indications focused on usability have been provided by Nielsen [7], [46]. They can drive both designers and engineers in the design and development phase and experts in the evaluation phase. They are ten heuristics considering:

H1 *visibility of system status*: the system must always allow the user to know the status of the activities in progress;
H2 *match between system and the real world*: the system must use a textual and non-textual language that is familiar and easy to understand;
H3 *user control and freedom*: the user must have control of the information content and move freely between the various topics;
H4 *consistency and standards*:all parts of the system must be consistent so it is good to define and respect conventions;
H5 *error prevention*: the design must avoid the lack of understanding that leads the user to make an error and always provide the function to cancel the operation or go back;
H6 *recognition rather than recall*:it consists of providing elements that facilitate the recognition of operations, minimizing the user's memory load;
H7 *flexibility and efficiency of use*: it suggests the possibility of a differential use of the interface (e.g. shortcuts), which take into account the user's expertise;
H8 *aesthetic and minimalist design*: it pushes for deleting all unnecessary elements, emphasizing the most important contents;
H9 *prevention of errors*: it focuses on providing the help to recognize, diagnose, and recover from errors, using simple, understandable language that indicates to the user how to intervene;
H10 *help and documentation*: to provide the user the necessary assistance when needed.

These heuristics are a guide for interface designers and can be integrated with additional specific heuristics driven by the case study. For each interaction expected between the human and the robot, regardless of the type of interface, it is possible to use this list of heuristics to verify that the HRCI meets all the requirements. If not satisfied, it means that designers must work to find ways to meet the missing requirements as essential indications to encourage good interaction.

3) Dimensions of interaction design: Aside to these general principles, interface design in HRC should also recall the five dimensions of interaction design [8], [47]. These dimensions refer to the communication language of a user interface. In particular:

IXD1 *Words*: they present in the interface, especially those that convey an interaction, should be essential, meaningful and easy to understand for the user.
IXD2 *Visual representations*: all the graphic elements (e.g. images, fonts, icons) of the interface supplement the words used to communicate information to users and to establish a content hierarchy.
IXD3 *Physical objects or space*: the objects through which the user performs the interaction (e.g. keyboard, mouse, touchscreen) and the space in which the user performs the interaction (e.g. train, home) greatly affect the interaction between the user and the product.
IXD4 *Time*: elements that change over time (e.g. sound, video, animations) are useful indicators for sending feedback and their aspect, pace and responsiveness influence the way in which a user interacts.
IXD5 *Behaviour*: the actions, reactions and emotions of the user resulting from the interaction define the quality of the interaction.

Moreover, the union of the fourth and fifth dimensions allow for further reading. The duration of the interaction affects the quality of the interaction both in terms of mental workload, but also of an increase in user expertise.

These dimensions highlight the main items to design also in the HRC context. Indeed, a HRCI has to create a collaborative work between humans and machines. For this purposes, the above-mentioned interaction dimensions are involved. Interfaces play a central role, as the main communication channel between the two entities involved (humans and robots) and generate different kinds of communication: from graphical language to voice-based communication, to gesture-based dialogue or physical/haptics interaction.

A designer can construct how a user communicates with the system based on these general interaction design principles. Some of the principles mentioned above, such as simplicity and clarity, are the basis of a good interface and become even more of fundamental importance in the industrial context.

B. Interaction design tools for HRCIs

From the analysis of the interaction design theory, this paper proposes a set of tools to be practically used for an efficient design of HRCI. For this reason four main tools have been identified. Two of them (i.e., Requirements Gathering Toolbox and User Journey) are useful to collect the information necessary for the design, while the latter (i.e., Wireframe Prototype and VR-based Prototype) methodically guide the design and provide a simulation of the interface use for design validation. In this context, it is useful to point out the importance of a multidisciplinary design team; in particular, only the close coordination between experts of interface design and software developers can guarantee the successful adoption of the proposed tools.

Fig. 2 presents an overview of the proposed interaction design tools for HRCIs and establishes a mapping between them and the theoretical principles discussed in Sec. III-A. In particular, the figure shows that a combined use of such tools allow to assess the compliance of a HRCI to all the interaction design principles.

1) Requirements Gathering Toolbox (RGT): Requirement gathering is the first phase of any user-centred design. In the context of HRCI, we propose a specific toolbox to collect data about the user interaction requirements to design HRCIs. Traditionally, there are various ways of gathering requirements, such as interviews, brainstorming activities, and focus groups. Anyway, the direct involvement of end users during the design phases is not always possible. Often there are no conditions to be able to carry out this type of activity, especially in the industrial sector. The proposed toolbox, shown in Fig. 3, is capable of taking into consideration the existing needs of users operating in the industrial sector. It is based on expert's analysis to overcome the limits due to the lack of involvement of end users, without neglecting the collection of valid and effective requirements. To facilitate and standardize the requirements analysis and data collection, as necessary for the design of HRCIs, four main areas of investigation have been identified:

- sequence of operations,
- communications,
- working conditions, and
- error situations.

These areas were considered to represent the essential contents to provide solid foundations for the design of HRCIs. With reference to Fug. 3, the first area (Sequence of operations) is based on task analysis and provides information about how the human actors are involved in the specific scenario; subsequently, the temporal sequence of the performed tasks are clarified and the reciprocal roles (if the activity is carried out by the human operator or the robot). This information should be as detailed as possible (e.g., entering the duration of each individual activity included into a complex task, differentiating whether it is monitoring activities or specific activities of the work cycle, or the activity effort level).

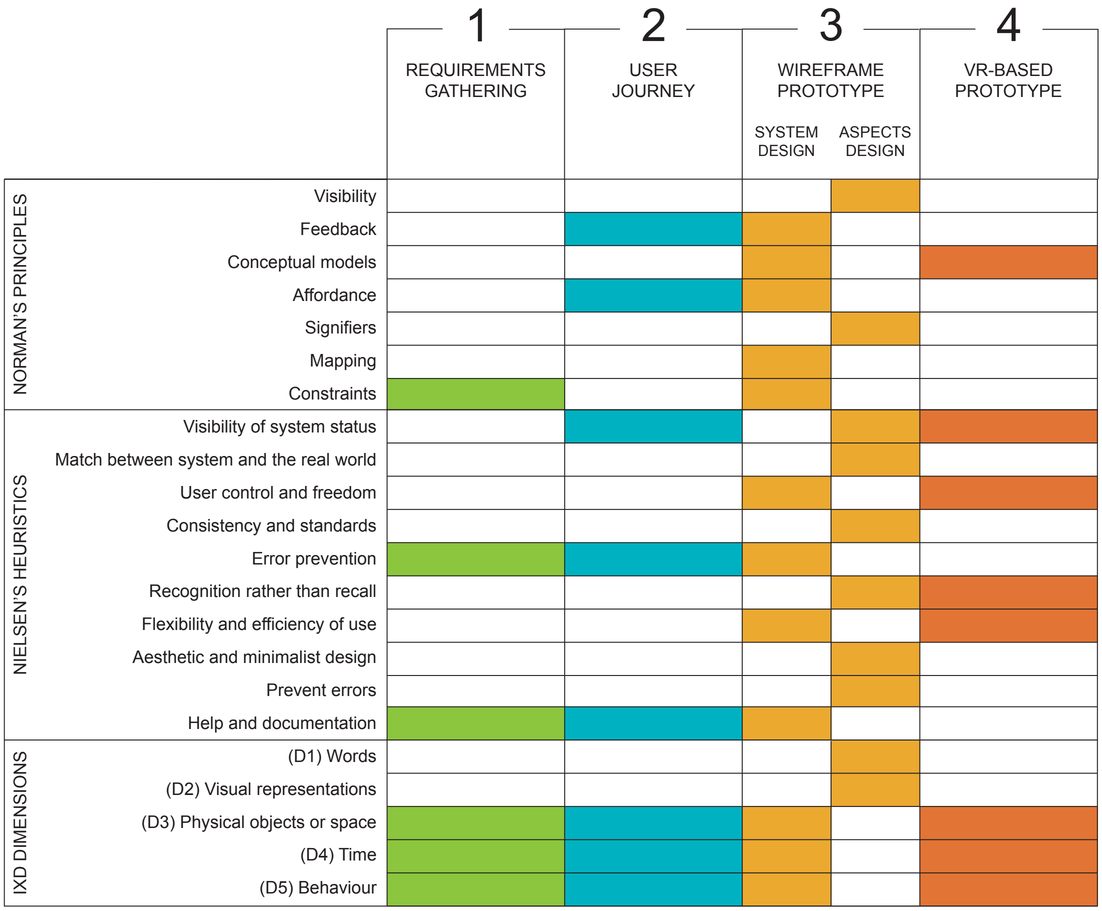
Once the sequence of operations is clear, communications can be investigated. The second area (Communications) refers to verbal or non-verbal exchange of information, considering three cases: exchange between operator and robot, between operator and system, or between operator and other operators. Designers must ask themselves which kind of inputs the operator must provide to other actors involved (e.g., a robot), which kind of feedback or data she/he must receive, and when/where communication takes place. All these aspects help in defining the most appropriate type of interface to use. For example, some interfaces are more suitable for a more complex information exchange, while others are more suitable for simple and repetitive interactions. In defining the moments of communication, the user's needs must be taken into account to map the scenarios of use and imagine how the interface will be used, considering what users want to get out of interactions.

The choice of the specific types of HRCI (e.g., visual displays, gestures, speech or natural language, physical interfaces), in combination with the type of communication, is bound to the working conditions. The third area (Working conditions) aims at describing the characteristics of the work environment where interaction takes place: from space typology, to space dimensions, presence of noises or vibrations, presence of dust, lighting conditions, and any other environmental condition (e.g., temperature, humidity). Furthermore, attention must be paid to whether users wear any personal protective equipment (PPE) like glasses, gloves, or helmet. The collection of this information is essential to understand the actual conditions in which the user will find her/himself at the moment of interaction, in order to prevent difficulties in using the interface.

Finally, the fourth area (Error situation) considers the normal conditions for carrying out the activities, according to the sequence described at the first step, and any possible errors that can occur. Indeed, interface must support the user interaction in normal conditions, but much more in extraordinary conditions. For this reason, designers have to think about the role of interfaces in case of troubles, failures or errors to collect a complete set of requirements, fully describing any possible interaction scenario. These considerations can lead, for instance, to the evaluation of dedicated error management strategies or interfaces. Different conditions will be then depicted in different use scenarios in the User Journey, as described in the following section.

What emerges from the collection of requirements is necessary to start the interface design. Any interface design is strictly linked to the specific case study, for this reason it is important to carry out a careful requirements gathering at the beginning of each project, with a solid reference to the context of use and the application scenarios. Even just a little variation in the environmental conditions can completely change the user interaction, and subsequently the user experience regarding the interface. The quantity and quality of informations that can be collected with the RGT leads to fill the gap generated by the lack of involvement of end users. Indeed, it focuses on the analysis of requirements information and, contemporarily, the evaluation of the situation as a whole, paying attention to the overall system activities and interactions among the different actors.

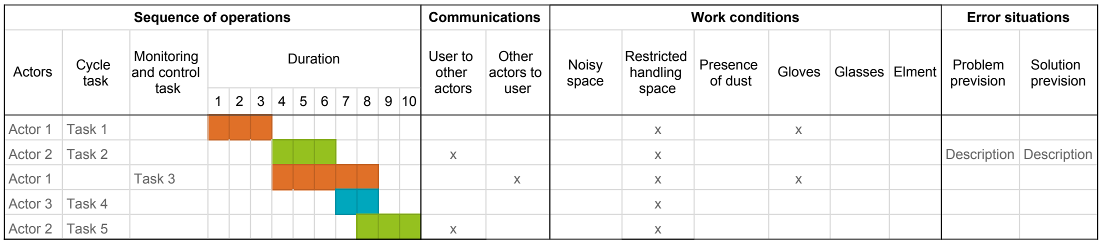
2) User Journey (UJ): After requirement gathering, it is useful to develop a visual representation that contains both



		1 REQUIREMENTS GATHERING	2 USER JOURNEY	3 WIREFRAME PROTOTYPE SYSTEM DESIGN	3 WIREFRAME PROTOTYPE ASPECTS DESIGN	4 VR-BASED PROTOTYPE
NORMAN'S PRINCIPLES	Visibility				🟨	
	Feedback		🟦	🟨		
	Conceptual models			🟨		🟧
	Affordance		🟦	🟨		
	Signifiers				🟨	
	Mapping			🟨		
	Constraints	🟩		🟨		
NIELSEN'S HEURISTICS	Visibility of system status		🟦		🟨	🟧
	Match between system and the real world				🟨	
	User control and freedom			🟨		🟧
	Consistency and standards				🟨	
	Error prevention	🟩	🟦	🟨		
	Recognition rather than recall				🟨	🟧
	Flexibility and efficiency of use			🟨		🟧
	Aesthetic and minimalist design				🟨	
	Prevent errors				🟨	
	Help and documentation	🟩	🟦	🟨		
IXD DIMENSIONS	(D1) Words				🟨	
	(D2) Visual representations				🟨	
	(D3) Physical objects or space	🟩	🟦	🟨		🟧
	(D4) Time	🟩	🟦	🟨		🟧
	(D5) Behaviour	🟩	🟦	🟨		🟧

principi-tools.pdf

Fig. 2. The proposed interaction design approach for HRCIs. Rows represent the interaction design principles that guide the design of HRCI from a methodological point of view. Columns represent practical tools that allow the compliance to principles during the design of HRCIs.



Sequence of operations													Communications		Work conditions						Error situations	
Actors	Cycle task	Monitoring and control task	Duration										User to other actors	Other actors to user	Noisy space	Restricted handling space	Presence of dust	Gloves	Glasses	Element	Problem prevision	Solution prevision
			1	2	3	4	5	6	7	8	9	10										
Actor 1	Task 1		🟧	🟧	🟧											x		x				
Actor 2	Task 2					🟩	🟩	🟩					x			x					Description	Description
Actor 1		Task 3				🟧	🟧	🟧	🟧	🟧				x		x		x				
Actor 3	Task 4								🟦	🟦						x						
Actor 2	Task 5									🟩	🟩	🟩	x			x						

Fig. 3. Template for RGT. Requirements should be gathered analysing the sequence of operations carried out by each actor involved in HRC, the communications occurring among them, the working conditions, and possible error situations.

the collected information and the activity flow carried out by each actor involved in the interaction. In fact, visualization is the most powerful tool to facilitate human reasoning and maintain focus on user experience [48]. For this purpose, the UJ is a specific application of journey maps to track the main moments of user interactions. Journey maps are widely used in traditional interaction design and service design to map interactions with a product, a service or a system, adopting the user perspective [49]. In this context, their use has been extended to describe the entire journey of the user during the sequence of operations, as analyzed in the RGT, for visually mapping the whole process of the activities carried out by all actors involved in a specific scenario. Actors can be human operators or different robots (e.g. anthropomorphic robots, cobots, automated guided vehicles). The visual representation, such as the one in Fig. 4, helps the definition of interaction states and thus facilitates the decision-making process.

The main items of the UJ are:

- Actors: involved each actor is represented in a column and associated to the others by a line. To speed up the identification of the actor, it may be useful to develop a representative icon for each actor;
- Task: for each actor, the tasks are represented in chronological sequence by associating each one with a short title to identify the activity;
- Interaction point: the points where the user interacts with other actors need to be highlighted, referring to the direction (if from the user to another actor or vice

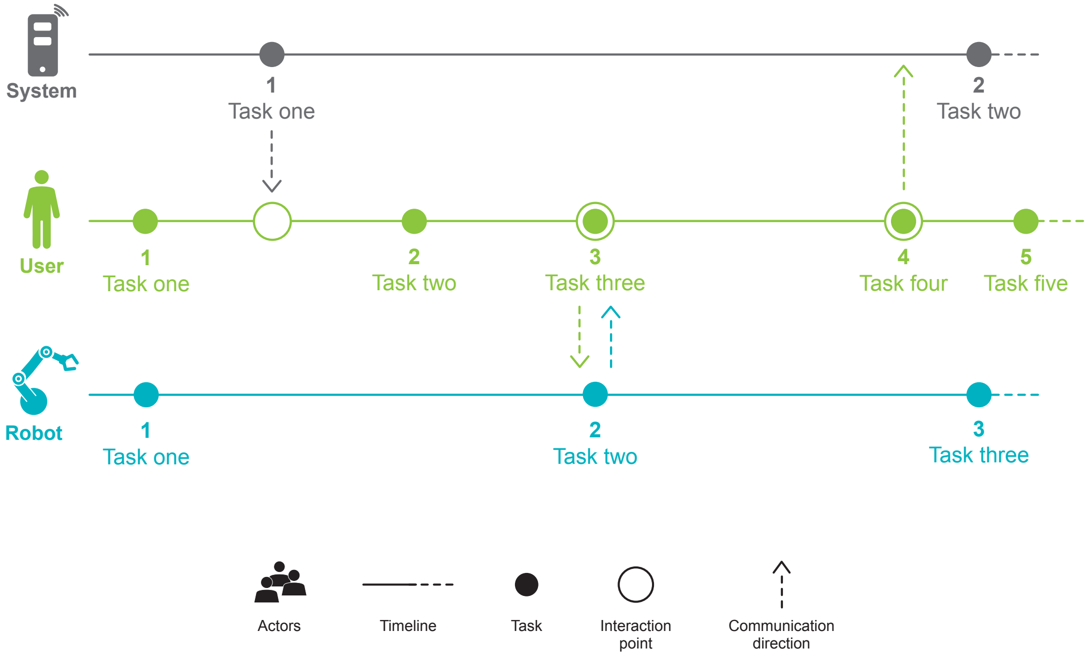


Fig. 4. Template for UJs.UJs allow the visualization of the intereraction process, by highlighting the involved actors, the tasks they are responsible and the exhange of information among them.

versa) and to the general action (e.g., confirmation of the end of the operation). The interaction points indicate the moments in which communications take place, as well as the moments in which an interface is needed.

As a result, the UJ highlights:

- who is the central user, considered for the analysis;
- how many other actors are involved;
- which the type and frequency of interaction are;
- what the complexity of interaction is.

For its nature, the UJ has to be necessarily updated continuously during the project design and development to check the appropriateness of the design choices. Moreover, various UJs can be developed based on the specific situation considered (e.g., normal performance of activities, problematic situation no.1, problematic situation no.2). UJs can be made with simple graphics tools or even simply on paper, so they do not require special skills. It is also a highly customizable tool that lends itself to be easily modified according to the needs of the scenario under analysis or to the preferences of the design team.

The UJ is a synthetic tool useful to highlight the communication moments between the central user and the other involved actors, especially when they are machines, computers or robots. Furthermore, it was found that the visualization of the process envisaged by this tool greatly facilitates the reasoning and collaboration by the whole team. For instance, visualization stimulates question and answers and pushes each member of the design team to unravel situations that are still not entirely clear. Furthermore, it gives incentives to consider situations that have not yet been considered or to think about different hypotheses for solving a problem. Even though it is not possible to directly involve end users into the user analysis phase, the UJ helps engineers and designers to adopt the user's point of view, focusing on what the user needs.

Finally, it is worth to consider that in HRC interaction can take place through numerous interface types (e.g. visual, vocal), as mentioned above; the choice must be guided by the information previously collected in the previous RGT and by the evidence that emerges from the UJ. The following step is the definition of the specific type of HRCI and the interaction process, for the preparation of interface prototypes. At first, the design of low-fidelity prototypes is useful to establish the architecture of the interface and its contents. Subsequently, high-fidelity prototypes can be realized to simulate the use of the interfaces within a virtual scene, as finale validation.

3) Wireframe Prototype (WP): RGT and UJ allow to set and describe how, when and where interaction takes place, which actors are involved and for what reason. After that, the HRCI must be prototyped and validated simulating its use, on the basis of the generated user experience. Prototyping is a fundamental activity for designers and engineers to concretize the project ideas and stimulate a critique reasoning [50]. In fact, the development of prototypes has always been a very stimulating activity and of great help in the design of any artifact (e.g. product, service) as they are united by the related design of the user experience [48]. In the case of visual interfaces, low-fidelity prototypes begin with the wireframe design (i.e. the interface design with simple lines). Wireframes are a set of documents that show the structure, hierarchy of information, functionality and content. This technique has its roots in architectural drawings and in network schemes but can be extended to include also other types of interfaces (as vocal or physical interfaces) describing the interface behaviours as labels in the wireframe.

In this direction, WPs allow the creation of low-fidelity prototypes, easy and quick to realize, to validate the interface design idea and ensure that the exchange of information takes place in an intuitive way and familiar for the user, without interfering with all other activities. A WP helps thinking about the organization of the system. In particular, it stimulates thinking about how many interfaces are needed, what the contents of each interface are, and their hierarchy and links. In defining the contents, it is necessary to detect what data and informations the user needs, what inputs she/he must send and what feedback is received, besides what buttons allow him/her to navigate the interface. Based on the type of interface, a WP allows defining the best way to realize the necessary interactions (e.g., using pop-up windows instead of dedicated pages), as well as thinking about how to divide the steps of the operation in order to not burden the user cognitive workload. Wireframes also promote to simultaneously think about the arrangement of the elements within the interface space, taking into consideration how the user will make of it (e.g. navigation buttons instead of radio button) [51].

Most of the time, this phase represents an iterative process of drawing and revisiting. For this reason, the most effective way to make a WP is with lapis and paper, or at least through simple software toolkits (e.g. Adobe XD, Invision, Sketch, Axure RP, Figma) that facilitate manual drawing and modifications. Once the main elements of the interfaces have been established, the WP can be further enriched by adding details such as colors, thicknesses and icons. When a final version of the WP has been reached, interaction can be simulated. Some software toolkits can also introduce the interfaces inside a device (drawn or modeled) and simulate the use of the interface as much as possible.

Although the WP is a low-fidelity prototype, it allows to check if the sequence of interactions provided is correct and if the workflow is adequate with respect to the expected usage. Specifically, design validation focuses on the following aspects: is the system setting clear to the user and immediately understandable? is the system easy to learn? are all the components necessary to navigate the interface included? is the communication direct and proper considering the use scenarios? Furthermore, with the development of this first prototype, the design team is able to promptly identify and solve any problems related to usability.

4) VR-based Prototype (VRP): For a more complete design validation, it is possible to move on to the development of higher-level prototypes. Unlike low-fidelity prototypes, high-fidelity prototypes require the use of specific computer-based simulations to replicate the real interface behaviors and provide a realistic experience. High-fidelity prototypes allow testing if the project meets the initial requests and the user's needs. In this context, the main difficulty is not prototyping the interface, rather considering the user experience within the specific working context. For this purpose, virtual scenes can allows designers to immerse in the simulation, acting as end users, and therefore to realize how user's overall experience will be. For this purposes, Virtual Reality (VR) can be used to virtually reconstruct the working environment and simulate the whole interaction process. Simulations can be totally virtual, where both humans and robots can be virtualized, or immersive for real users. In the second case, real humans are equipped with a head-mounted display (HMD) and specific sensors for motion capture, in order to be immersed into the virtual scene and interact with the digital simulation. In this modality, the members of the design team can act as real users and simulate the execution of user tasks, including moments of interaction with objects or other actors (e.g., robots, machines) involved in the case study. In this way, the sequence of actions and task duration can be easily checked, as well as ergonomics issues related to visibility, reachability or cognitive workload [52]. Moreover, virtual environments can faithfully represent a case study in a variety of contexts, also replicating problematic or dangerous situations in a safe manner. Another significant advantage offered by VR is the execution of user training before actually introducing the system on the market [53].

VR technology has been already used to simulate also human-robot scenarios and perform virtual testing, as also demonstrated by recent studies [54], [55]. In addition, VR can be also used to create controlled environments where users are monitored in order to understand the user experience and improve the final task performance. During immersive virtual simulation, users can be equipped with human monitoring sensors (e.g., biosensors, eye tracker) to collect physiological data to better study the human-machine interaction [56], [57].

IV. INDUSTRIAL CASE STUDIES

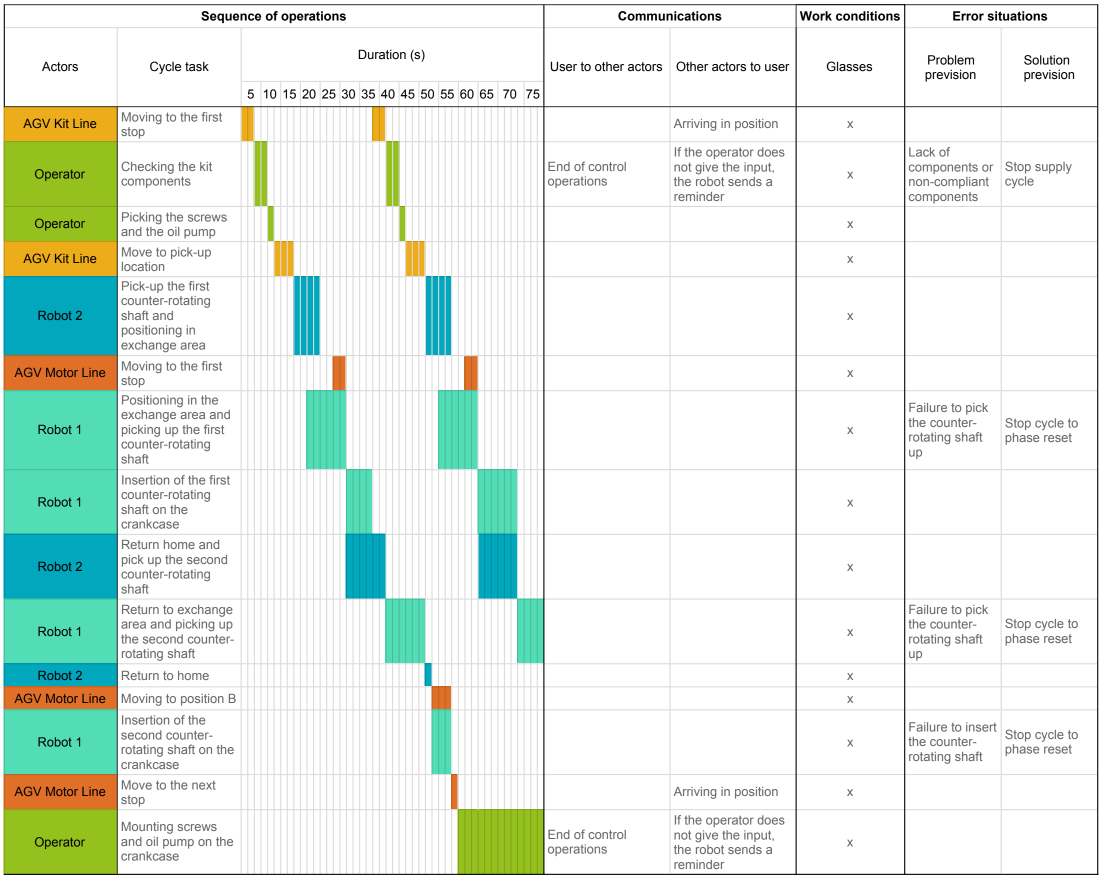
In this section, we will instantiate the proposed interaction design methodologies considering the two industrial case studies introduced in Section I.

A. Case study 1: Collaborative assembly of an engine

The scenario includes an assembly station with an operator, two Automated Guided Vehicles (AGVs) lines and two collaborative robots. One AGV line (Kit Line) is dedicated to the transport of the components to be assembled, while the other AGV line (Motor Line) carries the motor on which the robots and the operator will assemble the components. Specifically, one of the two robots is dedicated to the picking of the components (two counter-rotating shafts and assembly components) from the AGV Kit Line and subsequently passes them to the second robot that places them on the motor.

In this case study, the user has to communicate mainly with the AGVs when they stop at her/his position to allow him/her to pick up (from the AGV Kit Line) and place (on the AGV Motor Line) the components. Specifically, the AGVs need to communicate to the operator when they arrive at her/his station, while the operator needs to communicate to the AGVs when she/he has finished her/his tasks and the AGV can restart. These are the key information that indicate the point where the design of a dedicated interface is needed.

The detailed sequence of the operations carried out by the actors and the other information collected through the use of the RGT (Fig. 5) have been the starting point for the design of the interfaces. Subsequently, through the development of the UJ shown in Fig. 6, it has been possible to map more clearly and precisely all the communications that the interface has to manage. As can be seen from the UJ, only the main points of



Sequence of operations																	Communications		Work conditions	Error situations	
Actors	Cycle task	Duration (s)															User to other actors	Other actors to user	Glasses	Problem prevision	Solution prevision
		5	10	15	20	25	30	35	40	45	50	55	60	65	70	75					
AGV Kit Line	Moving to the first stop	■						■										Arriving in position	x		
Operator	Checking the kit components		■						■								End of control operations	If the operator does not give the input, the robot sends a reminder	x	Lack of components or non-compliant components	Stop supply cycle
Operator	Picking the screws and the oil pump		■							■									x		
AGV Kit Line	Move to pick-up location			■						■	■								x		
Robot 2	Pick-up the first counter-rotating shaft and positioning in exchange area			■	■						■	■							x		
AGV Motor Line	Moving to the first stop					■	■						■						x		
Robot 1	Positioning in the exchange area and picking up the first counter-rotating shaft				■	■	■					■	■						x	Failure to pick the counter-rotating shaft up	Stop cycle to phase reset
Robot 1	Insertion of the first counter-rotating shaft on the crankcase						■	■						■	■				x		
Robot 2	Return home and pick up the second counter-rotating shaft						■	■	■					■	■				x		
Robot 1	Return to exchange area and picking up the second counter-rotating shaft								■	■	■				■	■			x	Failure to pick the counter-rotating shaft up	Stop cycle to phase reset
Robot 2	Return to home										■								x		
AGV Motor Line	Moving to position B										■	■							x		
Robot 1	Insertion of the second counter-rotating shaft on the crankcase										■	■							x	Failure to insert the counter-rotating shaft	Stop cycle to phase reset
AGV Motor Line	Move to the next stop											■						Arriving in position	x		
Operator	Mounting screws and oil pump on the crankcase												■	■	■	■	End of control operations	If the operator does not give the input, the robot sends a reminder	x		

Fig. 5. Requirements Gathering Toolbox for the case study 1.

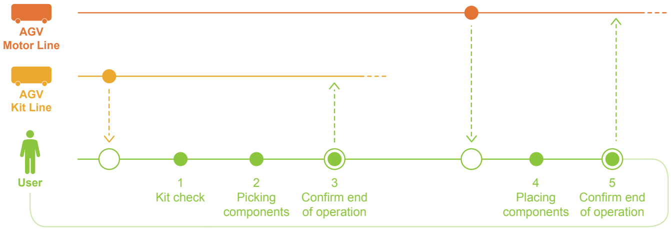


Fig. 6. User journey for the case study 1 for regular operating conditions.

the activities have been reported and the connections that the user has with the other actors involved have been highlighted.

The design process has led to the evaluation of introducing two interfaces, in order to allow the operator to better manage the exchange of inputs and feedbacks with the other actors. For communications with AGVs, the use of a wearable device has been considered, as it is an interface that lends itself to the exchange of simple and frequent information. While for the management of problematic situations a touch monitor would be more suitable as it facilitates the communication of more complex and articulated information.

Finally, a virtual reproduction of the scenario has been implemented. The virtual environment was developed in Unity (Unity Technologies, USA), a free game development platform with a built-in physics and rendering engine. The Oculus Rift headset (Oculus VR, USA) was used for immersive VR experience. The VRP shown in Fig. 7 allows to test the design hypotheses and have a more precise idea of what the user experience will be.

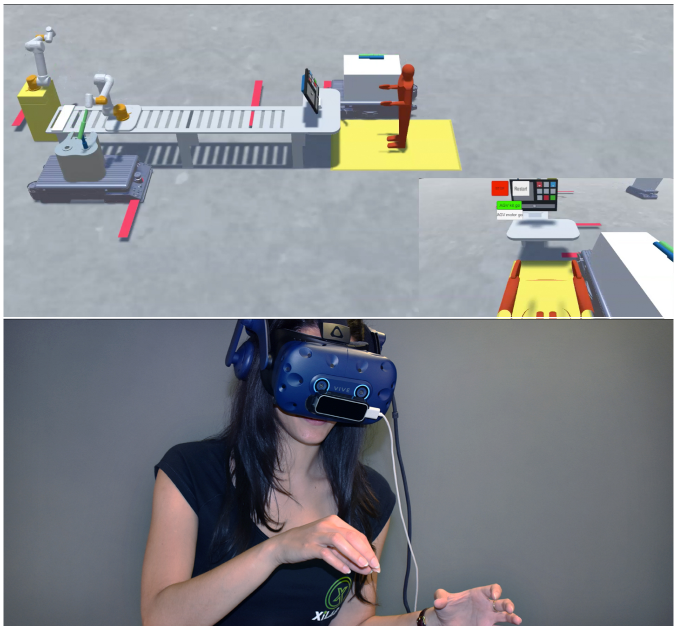


Fig. 7. Example of VRP for case study 1.

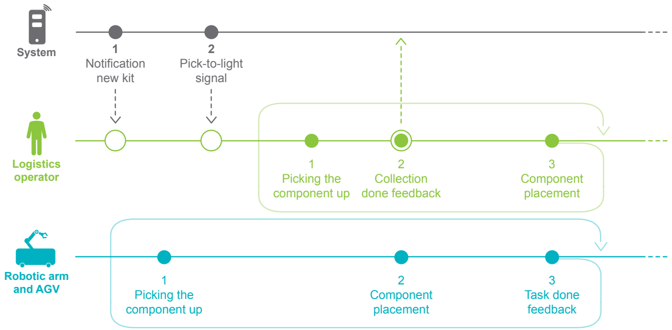


Fig. 8. UJ for the case study 2 for regular operating conditions.

B. Case study 2: Collaborative logistics

The second case study concerns a collaborative workstation within the logistics space of a production plant. In the shop floor area, two operators work on one side and two AGVs with a robotic arm on the other half. Both operators and robots are responsible for picking up various components from the shelves to compose an assembly kit. In particular, from the RGT and the UJs the need has emerged to design an interface that allows the operator to intervene if a problem occurs. In the event that a robot is unable to complete its task, a remote operator decides how to manage the situation, for example by commanding the robot to try again (Fig. 9) or ask the operator on the shop-floor to intervene (Fig. 10).

To tackle this error condition, the design of HRCI for a smartwatch has been considered. The development of wireframes has started from the information gathered and from specific communication needs. Through the design of the wireframes it has been possible to better understand that the interface could also be used to include other functions that would facilitate the operator's operations. In fact, as can be seen from the Fig. 11, the main screen provides visual feedback on the status of the activity that the user is carrying out. This simple visualization provides added value to the user experience as it increases user's awareness of the state of the work she/he is currently carrying out, as well as a guide for beginners. The interface of a smartwatch has the characteristic of being understandable at a glance and of sending messages with a few quick steps.

Also in this case, the VR has been of support during the design process. The VRP shown in Fig. **??** allows to visually recreate the context, the actors, the tasks and above all the communication and human-robot interaction.

The case study confirmed how VR prototypes can predict interaction between humans and robots, and support the validation of the interaction design.

Furthermore, in a case study like this where man and robots move freely in the same space, the use of VR can also be very useful to test the sensations that the user tries to be in contact with for the first time.

V. CONCLUSION

In this paper we considered the problem of defining the user experience in a collaborative robotic system, introducing

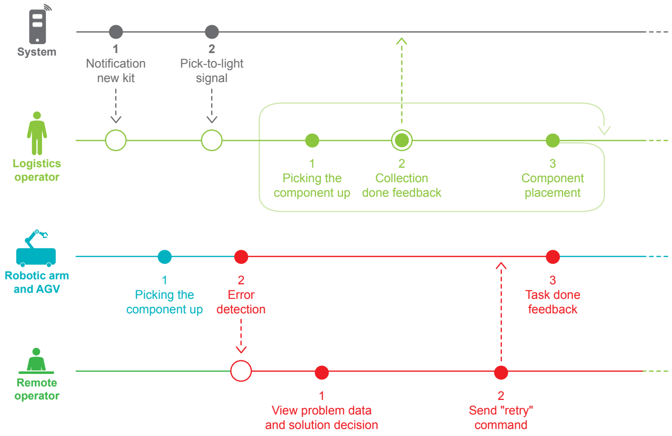


Fig. 9. UJ for the case study 2 in the case of the first considered problem situation: when an error is detected, the remote operator commands the robot to repeat the task.

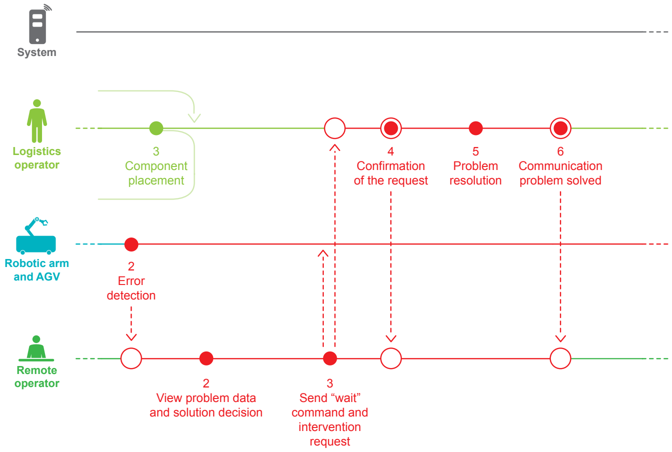
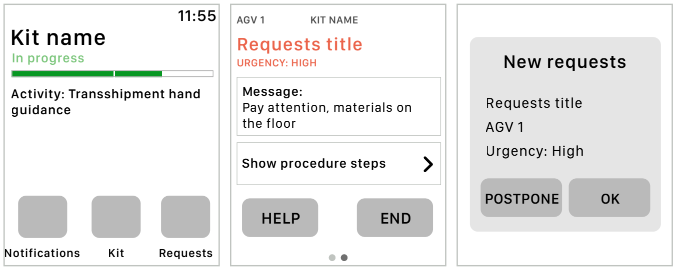


Fig. 10. UJ for the case study 2 in the case of the second considered second problem situation: : when an error is detected, the remote operator commands the logistic operator to repeat the task the robot failed.


11:55
Kit name
In progress
Activity: Transshipment hand guidance
Notifications Kit Requests

AGV 1 KIT NAME
Requests title
URGENCY: HIGH
Message:
Pay attention, materials on the floor
Show procedure steps
HELP END

New requests
Requests title
AGV 1
Urgency: High
POSTPONE OK

Fig. 11. Smartwatch wireframe example for the case study 2.

Fig. 12. Example of VRP for case study 2.

interaction design principles that are commonly used in the field of human-machine interfaces.

After providing an overview of the most well-known interaction design principles, we proposed a set of tools for their application in the considered domain. The proposed concept was then instantiated considering two representative industrial case studies.

The proposed tools provide different levels of abstraction, as well as different realization complexity. In particular, the WP provides a simplified view of the system, representing a time-effective tool for fast prototyping and early evaluation of user interaction and finally user experience. Conversely, the VRP represents a high-fidelity model enabling deeper evaluations of the human-system interaction. However, it is quite expensive and time-consuming to realize. Future work will aim at realizing the prototypes of the most promising design solutions achieved after expert validation, and user testing on the field on a wider range of case studies.

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