User-centered design for Human-Robot Collaboration systems

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Abstract. Autonomous robotic systems are one of the pillars of Industry 4.0, together with Digital Twin (DT) simulations and advanced Human Machine Interfaces (HMI). Customization requirements in modern manufacturing demand a closer collaboration between operators and automated technologies, leading to a novel Human-Robot Collaboration (HRC) and interaction paradigm aimed at the augmentation of human capabilities in the workplace. This scenario calls for a new definition of HRC standards and design for safety, programming, and an overall assessment of modern cyber-physical systems. A comprehensive design process aiming to formulate a common framework of requirements based on human, organizational and production needs is missing. A user-centered design approach described may be a solution to address the open challenges of future HRC. DT and Augmented and Virtual reality technologies (AR/VR) are implemented in elaborated model as the necessary tools to assign the operator a central position in the design, control, and assessment of modern industrial collaborative scenarios.

1. Introduction
The advancements in industrial automation and the need for flexible, adaptable production systems aimed at mass customization lead to closer collaboration between humans and robots in several industrial fields. Big data and analytics, autonomous robots, simulation, system integration, industrial internet of things, cyber physical systems, the cloud, additive manufacturing, Augmented and Virtual reality (AR/VR) are among the leading technology drivers for the industry 4.0 (I4.0) revolution [1]. Human-Robot Collaboration (HRC), in particular, is a crucial aspect in the evolution of modern industry into a scenario that will see human workers being empowered by sensing and perceptive technologies supporting and perfecting human skills throughout the production process [2]. Natural, adaptive, and intuitive Human Machine Interfaces (HMI) are necessary to enhance safe and efficient teaming processes [3], favoring well-being, and technology acceptance in the upcoming industrial scenario. Recent studies show an increased interest in Digital twins (DT) AR/VR interfaces with examples of assessment and evaluation of safety [4] programming methods [5] and commissioning of HRC systems. A few studies attempt the combination of DT AR/VR technologies in a User Centered Design (UCD) approach focusing on specific use cases. Businesses adopting I4.0 driving technologies are aware of the risks and impacts these have on the operators [6]. No clear design and assessment methods are yet available or enough to provide a robust framework that would include human factors in design and decision-making strategies related to HRC. This work aims at addressing the relationships and synergies occurring between the HRC process and a UCD approach for collaborative robotic scenarios. The main research question is whether DT AR/VR interfaces are valuable and reliable tools for the development of modern user-centered robot collaboration systems improving the efficiency and safety of interaction between operators and machines in the manufacturing field.
2. Evolution of HRC in 4.0

Teaming skilled workers and robots in complex tasks' execution combines the advantages of automation with soft human skills and decision-making [7]. Safety, intuitive interfaces, including input modes, outputs, feedback, and programming approaches, together with innovative design and control methods, are the main ingredients and challenges for the upcoming development and implementation of collaborative production technologies [8]. The forthcoming massive exploitation of collaborative robots will lead to a series of organizational, human-centered issues, and production process adaptations [9]. Close collaboration between humans and robots should be addressed by evaluating the impact these technologies have on the industrial environment and the operators. Individual, organizational and robotic agent factors influence the design and organization of the future workspace with open challenges such as operator monitoring, stress level, workload assessment, robotic system acceptance, efficient reprogramming, data management, ethics, and privacy related to the collected data [10]. The change in production paradigms will transform the role and type of relationship and interaction that human workers have with automated technology from mere cooperation to an augmented and symbiotic paradigm. In their study, Romero et al. [11] describe how the coming generation of industrial Operators 4.0 (O4.0) will be enhanced in their physical, sensorial, and cognitive capabilities, being at the center of a symbiotic cyber-physical system. The agents involved in this new production paradigm will need to be intelligent; therefore, purposeful, perceptive, aware, autonomous, able to act, reflective, adaptable, learning, and conversational. While many of these qualities are part of human skills, industrial robots seem to be far from achieving these characteristics.

The popularity of DT solutions and research applications is constantly increasing [12]. The plasticity of this technology is demonstrated by examples spanning from manufacturing applications, electric engine optimization [13] to building construction [14], aviation, and healthcare [15]. The scalability of simulation driven solutions allow for applications supporting maintenance and production planning [16] to specific realtimed data driven model for product monitoring [17]. AR/VR HMI for HRC offer the advantages of including the user as an active agent in a robotic cell's control interface, which is itself a DT of the controlled system and environment. Many recent studies focus on experimental approaches to DT AR/VR interfaces with applications aimed at programming [18], control [19], design of collaborative industrial cells [20], and HRC safety assessment [21]. Other examples address the potential of these technologies in becoming UCD design and evaluation tools for advanced industrial systems and workstations [6] [22]. The rising HRC industrial paradigms need to be tested and validated both in terms of HRI, interface efficiency for robot control and system impact on the user. What is missing is a systematic approach that would allow the evaluation of all aspects involved in the HRC process and make DT AR/VR interfaces the main tool bridging human and robots in a UCD approach.

3. Collaboration levels, safety and programming in HRC

Human-robot levels of collaboration can be defined in different ways. Helms et al. [23] describe four types of human-robot operations: independent or parallel work, synchronized work simultaneous work and assisted or collaborative scenarios. The last scenario involves humans and robots having a common task, sharing workpieces, tools and workspace while performing the required task at the same time. De Luca et al. [24] further specify the relation between safety, coexistence and collaboration defining them as nested levels of human-robot interaction (HRI). Safety is defined as the core feature of robots involved in collaborative working scenarios. Collaborative industrial robots' requirements are described in [25] and include four main safety modes: Safety-rated Monitored Stop, Hand Guiding, Speed and Separation Monitoring, and Power and Force Limiting. Regardless of the characteristics of each specific method it is crucial to keep in mind the type of involvement and level of physical contact that the operator has in each mode and the implications for both collaborative task performance and robot programming operations. Different interaction modalities need a clear definition of robot context-awareness by sensors and artificial intelligence and have a different impact on the operator. Programming is another central aspect of modern collaborative robots as it involves a variety of dedicated interfaces or direct manipulation methods such as in walk-through or programming by demonstration. Virtual reality (VR) might offer a possible solution for
some of the issues related to programming procedures by providing a repeatable controlled and safe environment for kinesthetic teaching procedures [26] also on the old generation of robotics systems.

4. UCD for HRC

The contemporary industrial production and O4.0 requirements in HRC need to be allocated in a design model able to organize collaboration, therefore task allocation and organization, safety and programming on the same design scope. A user centered design approach seems to be a valuable solution for this challenge. End-users within a UCD [27] must be active in an iterative design process involving planning, testing, commissioning, and assessment of the system. The design process should clearly allocate and define tasks between user and system and include multidisciplinary resources and skills both in defining the requirements and in the assessment phase. Examples of open and multidisciplinary approaches for the design of complex, intelligent systems, for example, can be found in autonomous driving vehicle design [28]. Moreover, requirements should be drawn by analyzing all involved stakeholders the context of use, including personal and organizational needs and objectives. This can be done by means of qualitative based descriptions and user models ethnographic research methods or quantitative data collection and analysis.

The new approach shown in Figure 1 aims at a comprehensive design solution for HRC by efficiently allocating safety, collaboration modes, interfaces, managerial and task-oriented issues and requirements in an iterative design and evaluation process revolving around the user and its context. The proposed method matches requirements and technologies typical of HRC systems with the UCD design cycle and specifications.

![Figure 1. A conceptual view to synergies between modern HRC systems and User Centered Design](image)

We propose that DT AR/VR interfaces will be the main technology driver for this new design method, the tool empowering the O4.0 paradigm and mediating human and robotic systems interaction. Real-time simulations and interaction technologies can assist in evaluating users, environmental, and organizational aspects by providing insights into the state of the system in all its aspects. DT AR/VR interfaces are grounding on IoT, advanced sensors, artificial intelligence, and data analysis technologies which are
promoting smarter safety systems and learning approaches in robotic collaboration and programming by grounding their advanced capabilities precisely on human and environment-based data and behavior analysis. Figure 2 shows the state of realization of the presented approach in the study case discussed in [29] demonstrating the centrality of DT AR/VR interfaces in assessing an efficient HRC system along a UCD workflow. In particular the prototype and assessment phases show the O4.0 paradigm of augmentation of control capabilities in the virtual simulation.

**Figure 2.** Workflow for human robot collaboration

5. **User-centered DT AR/VR architecture for HRC**

Considering the variability of collaborative design tasks, automated systems features, interfaces, safety, and programming methods, DT AR/VR interfaces allow for the efficient adaptation and scalability of these variables, including the human operator and the context of use as main players in the configuration of modern cyber-physical systems. VR supports the simulation of reproducible and controlled contexts of use and could potentially be adopted to integrate existing ethnographic research methods [30]. AR/VR technologies include motion and eye-tracking capabilities and can easily be integrated with environmental, physiological monitoring sensors, and motion tracking systems aimed at the description and evaluation of human factors. The use of DT based interaction methods offers a safe and effective approach for experiments on real machinery. The software integration model for a DT AR/VR based HRC systems supported by a user-centric design approach is presented in Figure 3.

**Figure 3.** Software integration for HRC systems based on DT AR/VR interfaces
The model contributes to a truly immersive VR/AR training and control system, which provides an agent with higher-level involvement than customary training and thus being more efficient in the HRC process. Moreover, there is a need to develop metrics for assessment and validation of HRI standards in DT AR/VR interfaces of manufacturing systems. The central point of the research is that the test methods and metrics for human-robot teaming should be developed first in DT immersive interfaces to increase the safety level of physical industrial robotic and overall manufacturing systems. The proposed architecture allocates evaluation of DT system performance, HMI efficacy and usability, impact on the user and HRI assessment.

6. Discussion
The evolution of advanced industrial systems, where the operator gains a central position in collaborative production scenarios, encourages more comprehensive and holistic design solutions. UCD can be adopted in supporting the optimization and evaluation of HRC cells by organizing and arranging its components and characteristic along an iterative process that would include human stakeholders, context, and organizational issues in the same design scope. DT AR/VR interfaces offer a new paradigm of interaction with robotic systems and support O4.0 capabilities augmentation in the workplace. Moreover, by including the operator in the interface and simulation itself, AR/VR technologies support the planning and evaluation of advanced HMI in HRC within a user-centric design method. UCD based on DT AR/VR interfaces could lead to more efficient production processes, industrial cell deployment, evaluation of psychological, physiological well-being, and ergonomics factors in HRI.

Extensive research is necessary to clarify the state of the art in DT AR/VR interfaces by addressing use cases, type of interaction, and evaluation metrics. Based on the DT AR/VR for robotic arm control and programming presented in Figure 2, future works will understand how AR/VR is linked to the DT loop and HMI process. User based experiments will try to understand how humans are involved in each interaction, with the robot, with the AR/VR technologies, and with the DT simulated interfaces, and which could be shared metrics of evaluation between these processes. Future research will address cybersecurity, connectivity methods (between physical and virtual worlds) optimization, and development of virtual distributed infrastructure with open access for experimental design environment with various machinery for system integrators and end-user as well researchers.

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