AR for Human–Robot Collaboration/Cooperation in Industrial Applications

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Augmented reality (AR): overlays virtual objects on the real-world environment and also provides the ability to interact with that environment. AR is any case in which an otherwise real environment is “augmented” by means of virtual (computer graphic) objects. With the continuously growing usage of collaborative robots in industry, the need for achieving a seamless human–robot interaction has also increased, considering that it is a key factor towards reaching a more flexible, effective, and efficient production line. As a prominent and prospective tool to support the human operator to understand and interact with robots, Augmented Reality (AR) has been employed in numerous human–robot collaborative and cooperative industrial applications.

augmented reality human–robot collaboration human–robot cooperation

1. Introduction

The personalized production paradigm that characterizes industry 4.0 allows customers to order unique products, with characteristics that the customer himself specifies. The linear, sequential and standardized production lines that emphasize the high productivity and product flow required by the last (third) industrial revolution no longer satisfy the consumer’s current needs and personalized demands. The industry, however, is not yet completely prepared to deal with this paradigm [1][2][3].

While matching this new trend and managing the demand for innovative products, industries are expected to keep high production levels without decreasing their product quality, to maintain relevance within a competitive market. To do so, a high level of production flexibility, decentralization of decision-making, and intelligent use of available resources are required to allow customized mass production without significantly increasing production costs [1][2][4]. Industrial automation alone is no longer enough to fulfill these new requirements. Traditional robotic systems alone are no longer suitable for every task that each production requires. This urge created a path for new technologies, such as collaborative robots and augmented reality, and concepts, such as human–robot collaboration and smart operator or operator 4.0, to emerge.

Even though factories are increasingly employing smarter and connected technologies, human workers still have a dominant role in the production process. Combinations of humans and machines have the potential to outperform either working alone since their capabilities complement each other. For example, humans can handle uncertainties that demand cognitive knowledge and dexterity while robots supply higher physical strength and precision. This duality leads to an idealization of a system where humans and robots combine strengths in a way that both contributors could make use of their values to support each other and not be limited by their conditions, and work towards achieving a common goal. This combination of working is addressed as Human–Robot Collaboration (HRC) [5].

To safely cope with human operators, industrial robots, working in a mechanized repetitive production line, are now being replaced by collaborative robots or cobots. The ISO 10218-2:2011 standard defines collaborative robots as robots designed for direct interaction with a human within a limited collaborative workspace. The same ISO defines a collaborative workspace as a common area within the safeguarded ground where both humans and robots can perform tasks simultaneously during production operations. [6] presents a comparison between traditional standard industrial robots and industrial collaborative robots, where the main differences between them can be summarized in three major points: the ability to safely interact with humans in a shared workspace, allocation flexibility (light-weight structure, smaller size), and ease of programming.

It is worth mentioning that robots are not collaborative per se. Instead, applications can be rendered collaborative by adopting adequate safety features. Moreover, the term “collaborative robots” suggests the erroneous idea that the robot is intrinsically safe to cope with the operator in all situations [7]. For example, a robot working with a sharp edge as an end effector continues to be dangerous even if working at a low speed and with limited torque.

There are plenty of different collaborative robots manufacturers currently on the market, for example, ABB [8], Kuka [9], Rethink Robotics [10], Universal Robots [11], COMAU [12], Franka Emika [13], Yaskawa [14], TECHMAN [15], among many others. Villani et al. [16] compiled and compared some models specifications in his work. Collaborative Robots can be utilized in numerous industrial applications such as Assembly (screwdriving, part insertion …) [17]; Dispensing (glueing, sealing, painting …) [18]; Finishing (sanding, polishing …) [19]; Machine Tending (CNC, Injection mold …) [20]; Material Handling (Packaging, Palletizing …) [21]; Material removal (grinding, deburring, milling …) [22]; Quality Inspection (Testing, Measuring …) [23]; Welding [24] and many more.

Understanding that the transition from a purely manual or automated production activity to a human–robot cooperative scenario must be done in a way that brings not only benefits to the manufacturing industry (less processing time, increased quality and control of production processes …) but also to the operators (improvement of working conditions, improvement of skills and capabilities …), Romero et al. [25][26], addresses the “smart operator” topic from a human–centered perspective of industry 4.0. The scholar defines Operator 4.0 as an intelligent and skilled operator who performs work, aided by machines if and as needed. Romero et al. [26] also describes the typologies of operator 4.0 that were compiled, later on, by Zolotová et al. [27], into the definition of:

- Smart operator: an operator that benefits from technology to understand production through context-sensitive information. A smart operator utilizes equipment capable of enriching the real-world with virtual and augmented reality, uses a personal assistant and social networks, analyzes acquired data, wears trackers and works with robots to obtain additional advantages.

According to Milgram and Kishino [28], Augmented Reality (AR) is in between real and virtual reality (VR), thus being considered a mixed reality technology (MR). They define AR as a real environment "augmented" by means of virtual (computer graphic) objects. Azuma [29] defined AR to be any system to have the following properties, which avoid limiting AR to specific technologies, such as head-mounted displays, as previous scholars did:

- Combine real and virtual objects;
- To be interactively and in real time;
- To be registered in three dimensions.

Thus, it is possible to rewrite this definition as a technology capable of enhancing a person's physical environment perception through interactive digital information virtually superimposed on the real world.

Despite not totally mature for every industrial applications due to hardware factors such as ergonomic aspects like weight and movement restraint, which do limit the number of components and features that a visualization equipment can have, due to software factors such as tracking and recognition technology limitations, lack of standards on applications development and on how and which information should be displayed to the user, as well as due to being a new technology yet to be fully integrated into enterprise resource planning systems (ERP) and manufacturing execution systems (MES) [30][31], AR has been used in plenty of different industrial applications such as: Assembly support [32]; Maintenance support [33]; Remote assistance [34]; Logistics [35]; Training [36]; Quality Control [37]; Data visualization/feedback [38]; Welding [39]; Product design/authoring [40]; and Safety [41] among other applications including Human–Robot Collaboration that will be discussed next. Thus, proving that AR is a promising tool to increase the operator's performance and safety conditions, increase activities execution speed, decrease the error rate during task execution, rework and redundant inspection, and reduce mental workload.

Another important requirement of AR applications is the activation and tracking method, which can be divided into two main categories: marker-based and markerless systems. As the name implies, the main difference between the two technologies is that the first relies on fiducial physical markers, such as QR codes, for example, to be positioned where it wants the virtual information to be anchored and exposed to the user. Although this method tends to be easier to implement, it can suffer in industrial environments due to dirt, corrosion, and poor light conditions. In contrast, markerless systems do not depend on fiducial markers; instead, they rely on objects natural feature tracking, such as borders and colors, which require a much higher processing capacity due to the more computationally intensive, complex, and elaborated detection algorithms, and can also be affected by poor light conditions. For example, one markerless tracking could continuously scan the environment and compare each frame to a CAD model to find a similar pattern or a gesture, whereas a marker-based tracking system scan for a single specific predefined pattern that will trigger the virtual information to be rendered and shown to the user [42][43]. Moreover, tracking systems are important to ensure the accuracy and repeatability of mixed reality systems, which is indispensable for some applications, such as programming by demonstration [44].

With the continuously growing usage of industrial collaborative robots, the urge for achieving a seamless human–robot interaction has also increased. Seamless cooperation between a human operator and a robot agent is a key factor to reaching a more flexible, effective, and efficient production line by reducing the number of errors and time required to finish a task while improving the operator's ergonomics at work, lowering its cognitive load, enabling decentralized decisions and making better use of available resources.

As a prominent and prospective tool for aiding human operators to understand robots' intentions and interact with them, Augmented Reality, is expected to fill this gap and solve the "human in the loop" integration problem by augmenting information properly into the operators' field of view and acquiring its inputs to the cyber-physical system. AR has been demonstrated to be effective for Human–Robot Interaction in numerous fields of applications such as: Assembly guidance [45][46]; Data visualization/feedback [47]; Safety [48]; Programming/authoring [49][50], and so on. The growing market expectations of both technologies [51][52] corroborates with the upward tendency in the number of research papers towards the field of augmented reality human–robot collaboration.

2. Augmented Reality for Human–Robot Collaboration and Cooperation in Industrial Applications

This analysis was used to answer the three research questions: (Q1) What are the main AR visualization technologies used in industrial Human--Robot collaboration and cooperation context? (Q2) What are the main field of application of AR in industrial Human--Robot collaboration and cooperation context? and (Q3) What is the current state of the art of AR applications for Human--Robot collaboration and cooperation? Is research focusing on experimental or concept applications? What are the most used assessment techniques and indicators? What are the Research gaps presented in AR for industrial Human--Robot collaboration and cooperation context?

The first major contribution of this paper is the identification of the main AR visualization technologies used in industrial human--robot collaboration and cooperation context (research question Q1). HMD interfaces have gained relevance since 2018, followed by a not as much exponential interest growth of projected interfaces. On the other hand, Fixed Screen and HHD interfaces have fallen into disuse for HRC applications in the past three years. As mentioned by De Pace [4], these results are not unexpected: HMD and projector-based interfaces are hands-free, which enable greater operator mobility within the industrial warehouse and does not require as much attention shift as Fixed Screen and HHD approaches.

It is acceptable to assume that these characteristics would allure researchers to focus new studies on these two interfaces, especially on HMD. Moreover, since newer headsets are capable of performing scene understanding and natural gesture interactions without the need of external devices, it is expected that the research interest of this devices quickly grows. The same argument is valid when comparing the Augmented Reality glasses. Neither the Epson MOVERIO[53] nor the Acesight S[54] do not provide the same capabilities as the Microsoft HoloLens[55], which explains the researchers' preference for using the Microsoft device. Therefore, the exponential growth of studies involving HMDs can also be related to the first version of the Microsoft HoloLens in 2016.

Comparing the projector types used for Human--Robot collaboration, there is not a clear preference towards a particular projection method. Even though brightness, resolution, contrast, and other factors must be taken into consideration when choosing a projector, the selected papers lead to a faint tendency towards LCD and LED approaches.

Although all HHDs were based on Android, it is not possible to assume this operating system as a preference due to the small sample size. Some factors that may justify the inclination of researchers towards Android are the potentially lower cost, the larger number of platforms and devices, the easier adoption for developers, and the APIs to take full advantage of the embedded sensors.

Concerning tracking methods, there is a tendency to use markerless approaches. That is mostly driven by projection systems, which use feature extraction software for tracking object positions. However, marker-based approaches are gaining strength, especially due to the HMDs. The straightforward implementation of marker-based approaches and the lower computational power required might be the reasons that sustain this increasing tendency. On the other hand, the new Augmented Reality HMDs have a reasonable computational power and numerous sensors and cameras for spatial mapping, which may favor the use of markerless approaches over time.

The second major contribution of this paper is the identification of the main fields of application of AR in industrial human--robot collaboration and cooperation context (research question Q2). The use of augmented reality for improving the operator's awareness, trust, and safety feeling towards the robot is a constant concern, making the safety category the most researched one. Since the operator needs to share the workspace with one or more robots, any additional layer of safety may help improve the operator's condition and feeling towards the robot and the collaborative scenario. Although no Augmented reality safety approaches are yet certified, some of them have been showing promising results as active monitoring systems.

The capacity of augmented reality to display real-time information to the user field of view is essential to insert the human in the loop. Providing production live status, graphics, simulations, analysis and other operation-related information in a fast and intuitive way enables the user to be more assertive when making a decision that can affect the whole production line, or responding to emergencies.

Moreover, by showing to the user step-by-step text, images, videos, 2D or 3D representation of a workpiece, or animated instructions, augmented reality is vastly used for guidance applications. The main contributions for guidance applications are improving the operators' performance by reducing the task completion time and abstracting the user of the necessity of memorizing numerous instructions for a variety of products, lowering their cognitive load, and enabling an untrained operator to be able to conduct any operation if needed. Augmented reality is also being vastly used for programming applications. Most of the applications developed in this field fall under the Human--Robot Interaction category since no further collaboration happens among the parts after programming. Finally, quality control is an area that is starting to be combined with augmented reality and is expected to gain more relevance over time.

Regarding the economic activity, the automotive industry conducts the largest number of studies by a considerable amount. This may be because the automotive industry has always been a pioneer when comes to testing emerging technologies and especially to the fact that it presents numerous challenges that are a perfect fit for evaluating different applications, from a smaller to a larger scale. Lastly, again by a large difference, assembly operations are the most studied activity when it comes to augmented reality applied for human--robot collaboration and cooperation.

The third major contribution of this paper consists of the identification of the current state of the art on AR applications for Human--Robot collaboration and cooperation (research question Q3). It is possible to infer that qualitative evaluations are currently more employed than quantitative evaluations. It indicates some uncertainty about the usage of Augmented Reality wearable equipment, especially on human--centered perspectives, such as usability and ergonomics terms. The most used evaluation techniques are the System Usability Scale (SUS) questionnaire, for evaluating the system usability, and the NASA-Task Load Index (NASA-TLX) questionnaire, for assessing the participants' cognitive load. On quantitative evaluations, the most used measurement is the task execution time, for assessing performance improvements, and the Rapid Upper Limb Assessment (RULA) technique, for evaluating ergonomic aspects.

AR applications demonstrated the ability to improve operators' performance, accuracy, task understanding, safety feeling, and task awareness when compared to baseline assistance methods, such as printed and fixed screen based instructions. Moreover, the change of purely manual tasks to an AR-assisted collaborative scenario was demonstrated to reduce the production cycle time and improve the operator's ergonomics. Concerning visualization, HMDs are deferred due to hardware aspects such as narrow field of view, occlusion, and weight, which might exert some influence on the operator's safety feeling.

Industries will soon employ AR applications for a variety of cooperative and collaborative tasks. Therefore, future developments should rely on end-user experience and feedback to further improve human--robot collaboration features. Moreover, multi-agent communication and interaction between different operators, devices, and services should be explored to promote more dynamic information exchange throughout the industry. Thus, there is still much development and research to be done and questions to be answered before understanding and achieving the full potential of Augmented Reality on Human--Robot Collaboration and Cooperation.

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