A Functional Taxonomy of Visual Augmented Reality for Human-Robot Interaction

Ornnalin Phaijit
University of New South Wales
Sydney, Australia
l.phaijit@unsw.edu.au

Mohammad Obaid
Chalmers University of Technology
Gothenburg, Sweden
mobaid@chalmers.se

Claude Sammut
University of New South Wales
Sydney, Australia
c.sammut@unsw.edu.au

Wafa Johal
University of Melbourne
Melbourne, Australia
wafa.johal@unimelb.edu.au

***Abstract*—Augmented reality (AR) technologies are today more frequently being introduced to Human-Robot Interaction to mediate the interaction between human and robot. Indeed, better technical support and improved framework integration allow the design and study of novel scenarios augmenting interaction with AR. While some literature reviews have been published, so far no classifications have been devised for the role of AR in HRI. AR constitutes a vast field of research in HCI, and as it is picking up in HRI, it is timely to articulate the current knowledge and information about the functionalities of AR in HRI. Here we propose a multidimensional taxonomy for AR in HRI that distinguishes the type of perception augmentation, the functional role of AR, and the augmentation artifact type. We place sample publications within the taxonomy to demonstrate its utility. Lastly, we derive from the taxonomy some research gaps in current AR-for-HRI research and provide suggestions for exploration beyond the current state-of-the-art.**

***Index Terms*—Augmented Reality, Human-Robot Interaction, Taxonomy, Literature Review**

I. Introduction

Augmented reality (AR) has been introduced to human-robot interaction (HRI) in the last decades as a method of integrating the real and virtual worlds. As defined by Azuma et al. [1], AR aligns virtual elements with reality in the real environment, in real time, and allows for interactivity. This therefore, makes AR ideal for enhancing the way a human and robot interact. The rising prevalence of AR systems in HRI can be demonstrated by the International Workshop on Virtual, Augmented, and Mixed Reality for Human-Robot Interaction (VAM-HRI), which has been running annually since 2018. For robust advancements in the field of AR-for-HRI, it is crucial to be able to identify the main components and the core skeleton of the field. Classifying the vast number of AR-HRI practices provides a concise view of the role of AR in HRI and can therefore deepen our understanding of it.

An overview of how AR was used in robotics over the period from 2015-2019 was presented by Makhataeva and Varol [2]. They classified cases into categories of robotics domains of application. However, how information was conveyed to users and how the user interacted with the robot were not emphasised or classified. The focus of the paper was on the categorisation of robotics applications and not the role of AR in robotics.

Milgram and Colquhoun [3] provided a taxonomy for Mixed Reality (MR) display systems according to three characteristics: real-virtual continuum, centricity and congruence. The real-virtual continuum ranges between a completely real, non-modelled environment and a fully modelled environment. Centricity describes the viewpoint that is shown in the display to the user with one end of the scale being egocentric and the other being exocentric. The last characteristic of the taxonomy is the control-display congruence which describes how directly and well-aligned are the display and the control with each other. Using this taxonomy, Milgram and Colquon were able to identify where common AR applications fit between the three characteristics. Although this framework provides an effective guideline for researchers to understand the different elements and possibilities within mixed reality, it does not classify the augmentation and its functional role. Moreover, no information regarding the entities being modelled was taken into account.

Offering a perspective on the functional role of AR, Hugues et al. [4] presented a functional taxonomy of AR environments. They highlighted two distinct classes - one which focuses on improving our understanding of the real environment, and the other which merely adds a virtual environment not based on reality. This provides an important distinction between the different functionalities of AR, but is insufficient in the context of HRI because it does not describe the role of AR *for* the robot, or provide an HRI-centric function classification.

Williams et al. [5] provided a taxonomy of Mixed-Reality Interaction Design Elements that focuses on the field of HRI. The three principle categories are: User-Anchored Interface Element, Environment-Anchored Interface Elements and Virtual Artifacts. The first group involves anchoring the virtual element on the user's display. In the second group, interface elements are anchored to the robot or the environment. The last category represents interface elements which can move on their own or be moved by the human or the robot. The authors also provided another taxonomy in the form of a reality-virtuality interaction cube. The three axes of the cube are the reality-virtuality continuum as introduced in [3], the flexibility of control (FC) and the expressivity of view (EV). The cube highlights the extent of improvement to FC and EV by VR/AR. Although this framework provides an insightful perspective of the interactive systems within VR/AR, we want to extend and describe the utilities of AR in HRI. Moreover, we want to extend the categorisation of AR to accommodate the role of the robot.

In this work, we give an overview of current HRI styles including how AR fits into the field, and present a multidimensional taxonomy of AR in HRI. Our work complements previously published taxonomies by including: the type of perception augmentation, the functional role of AR and the type of AR artifacts. We then categorise the most highly cited publications in AR-for-HRI within the proposed taxonomy. These categorisations serve as an assessment tool for the functionality of AR in HRI and provide a checklist for future HRI researchers to find new research areas that explore novel functionality for AR in HRI.

II. A Comparison of Human-Robot Interaction Styles

Two decades ago, Rekimoto and Nagao [6] introduced a perspective of how AR can extend our way of interacting with technology and real-world context. Their article illustrated the bi-directional interaction styles that users have with traditional graphical user interfaces (GUI), ubiquitous computing interfaces, virtual reality interfaces, and the newly (back then) augmented reality interactions. Their work aimed to enhance the user interactions with real-world environments by utilizing the situational awareness advantage that AR offers in real-world contexts. Since then, the field of AR has advanced to a large extent addressing several domain areas and interaction modalities that serve our everyday lives. With the advent of robots taking part in our real-world environment, it is a logical step to extrapolate on the role of AR within human-robot interaction (HRI). Thus, we propose a future outlook into the bi-directional interaction styles that can take place between user(s), the real-world, and a robotic entity or entities; as illustrated in Figure 1. This set of HRI styles was built as an extension of the HCI styles proposed by Rekimoto et al. [6] in order to situate augmented HRI relatively to other style of interactions.

a) Kinesthetic Interaction: occurs when human and robot directly interact without any computerized mediation [7]. For example, this is the case when a robot is used to render haptic feedback [8], when the robot adapts to human social proxemics autonomously [9], [10], or when a human physically moves the robot, for example when programming by demonstration (PbD) [11].

b) Graphical User Interface (GUI): The vast majority of robot platforms offer a GUI to mediate interactions between the human user and a robot. This enables users to communicate and interact with a robot, using a set of predefined commands or authoring tools that make it possible to interact without needing to know the technical/programming details behind the scenes. A classic example used by researchers in HRI is the Aldebaran Choreograph GUI to interact with a robot in a real-world context; in particular it is used in many occasions to run a robot using a WoZ approach, e.g. a NAO robot in an educational setup [12], [13]. GUI are often deployed on tablets to facilitate the interaction and compensate for non-robust NLP. Some robots even embed such tablet (e.g. Pepper, Kompai, and Jibo). Though a GUI can be powerful, it still introduces an interaction gap between the user and robot, as there is no direct interaction between the two and always needs to be mediated by a computer. Besides, it can lead to an attentional split which can increase the user's cognitive load [14].

c) Teleoperation: A dominant field of HRI is the teleoperation of robots. Generally, teleoperation tasks are performed from a distance, where the user is not co-located with the robot in the real-world, thus creating several interaction challenges. The user experience is more immersive when the computer system to operate the robot is co-located in the robot's real-world environment. An example of research work in this area can be seen here [15]. Various types of controllers have been investigated to make the teleoperation efficient and natural for the operator [16].

d) Internet of Things (IoT) Mediated: IoT technologies, such as sensors, have paved the way for robots and users to interact in the real-world via multiple connected channels, thus creating a shared space or environment with continuous access/exchange of information. IoT mediated interaction has opened up a number of application areas in HRI as shown in the review of the field by Simoens et al. [17].

e) Simulation: Generally, in a simulated environment that includes a robotic entity, the user plays a passive role when it comes to interactivity. Very limited interaction between the robot and the real-world takes place, and most systems rely on pre-defined parameters to generated robot simulations. USARSim [18] and ORCA Hub simulator [19] are examples of such a simulation system allowing interactions between human and virtual robot.

f) Virtual Reality (VR): An interactive virtual environment can host a robotic agent and a user to work on a task, thus creating an immersive virtual space for human-robot interaction. One of the main characteristics that enables a seamless interaction is the user's sense of presence and co-existence while interacting with a robot in VR. Unlike augmented reality environments, immersive VR environments allow very little or limited interaction with real-world entities. Examples of HRI studies that are enabled in VR environments can be seen here [20], [21].

g) Augmented Reality (AR): AR enables the superimposing of digital content on the real-world environment. Coupling that with a robotic entity opens a wide spectrum of scenarios and applications in HRI. Research in using AR in HRI is emerging [22], and brings many questions that relate to the interaction styles. One of the key questions is shaping the

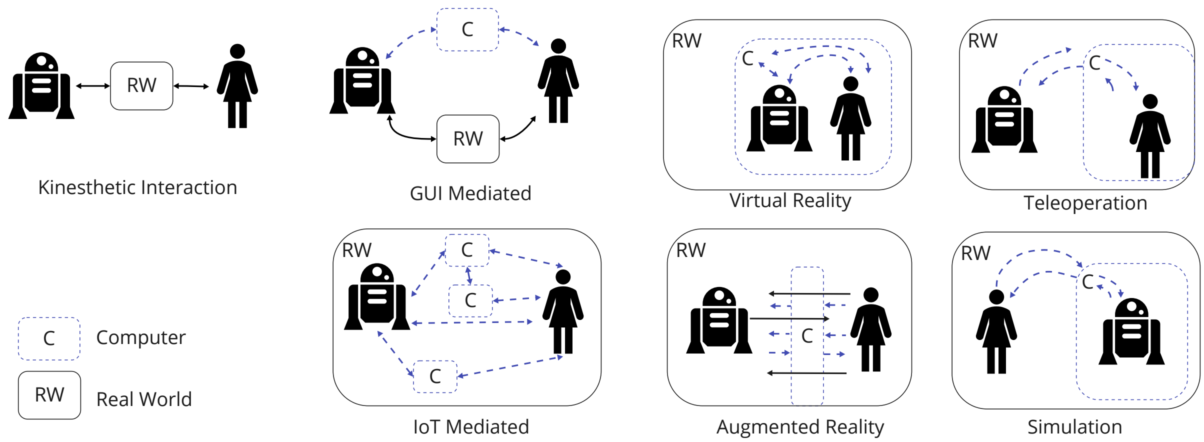

Fig. 1: A comparison of HRI styles - extended from [6]: Kinesthetic Interaction, Graphical User Interface, Teleoperation, Internet of Things, Simulation, Virtual Reality and Augmented Reality

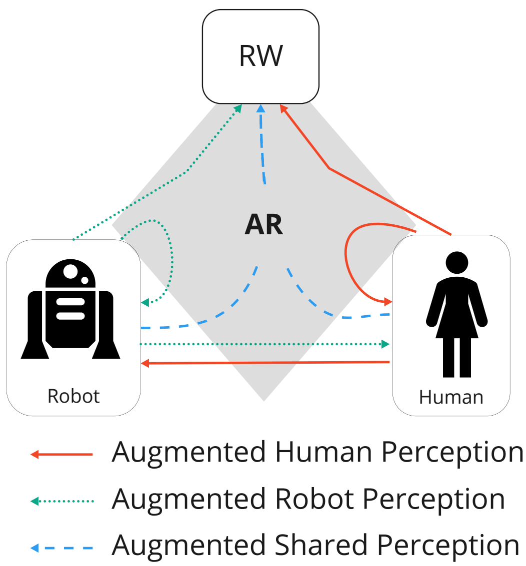

Fig. 2: Taxonomy of Perception Augmentation in AR for HRI: Perception Augmentation can be divided into Augmented Human Perception and Augmented Robot Perception. Within these categories, there exist further subcategories concerning the objects of perception: the robot, the human and the environment (RW: real world). We also envision AR to be a tool to build a shared perception and understanding of the environment

interaction and relationships between the user, the robot, the digital content and the real-world. In this paper, we focus on AR in HRI, where we unfold key interaction styles that can take place in that space.

III. Classification Based on Perception Augmentation

The goal of augmented reality as a human-robot interface can be to provide additional information to the human or the robot, or both. Extending the taxonomy presented in [4], we propose a taxonomy of AR for HRI that categorises the types of augmentation. As defined by Sydhagen [23] and suggested by Goldstone and Barsalou [24], perception is the acquisition of information, whilst cognition is the making use of this information. Therefore, this taxonomy shall use the term perception for the acquisition of information via AR. Figure 2 represents the proposed taxonomy of augmentation in AR for HRI. By acting as a medium for the transfer of data to an entity, AR augments the perception of said entity. Thus, the purpose of augmented reality can be divided into two categories: 1) to augment human perception, or 2) to augment the robot's perception. Note that augmentation of perception of both members may occur simultaneously.

A. Augmented Human Perception

Augmented human perception modifies the perception of the human by AR. However, which part of the human's perception is augmented? In the context of HRI, this category can be subdivided to accommodate the three entities involved in a typical HRI task: the human, the robot and the environment. The AR's role may be to augment the human's perception of self, the robot or the environment.

Augmented human perception of the robot: In this augmentation, the information given to the human via AR is in regard to the robot. This includes giving the user additional understanding of the robot's mental model. By using AR, the robot can convey information about itself explicitly to the user rather than using other modalities. In [25], the robot learns a bottle-opening task from human demonstrations and informs the user of its learning state by visualising its decision-making graph. In [26], a robot wheelchair displays obstacles in the user's desired path to paint a picture to the user as to why the planned path must be changed. In [27], the live camera feed of the robot is shown on the AR display whilst also showing the robot's real-time 3D reconstruction of the environment. Virtual arms can also be added to the robot to express its emotions to the human [28] and hence augmenting its social capabilities. Using AR, the user is able to better understand the robot's internal state and decision-making.

Augmented human cognition of the robot is not limited to providing the robot's mental model, it can also be used for the human to perceive the robot differently. An example is when AR is used to overlay a human avatar on a robot arm to provide affection to the user [29].

Augmented human perception of the environment: Virtual objects are presented to the user's display to provide additional information about the user's environment. Hugues et al.'s functional taxonomy for AR [4] falls under this category as it focuses on the augmentation of environmental information. The authors make an important distinction between augmenting the perception of reality and creating an artificial environment. The former involves visualising information that already exists, which the human may or may not be able to perceive. Both of these scenarios fit into this class. In [30], the robot performs point cloud change detection in the environment and visually highlights these changes to the user. The role of AR in this scenario is to enable the human to perceive information that exists in reality. The latter category of artificial environment enables the user to visualise information that does not and may never exist in reality. In [31], AR was used to visualise an artificial environment to set up a pick-and-place game between the robot and the human.

Augmented human perception of self: Just as AR can augment human perception of the robot and the environment, it can also modify the self-perception of the human. This includes providing feedback to the user of his/her actions. In [32], the command given to the robot by the user is shown as text on the AR display. In [33], AR was used to visualise the user's air-drawn model for a 3D robotic printing task. Augmented human self-perception is not only limited to actions, it can also include knowledge about the human's state. In [34], a virtual fence around the user is shown in the AR display. The colour of each part of the fence reflects the human's proximity to dangerous zones such as the robot's operating area. With this augmentation, the user is able to make judgements about her/his level of safety.

B. Augmented Robot Perception

AR enables the transfer of additional perceptual information to the robot. As the scope of this paper is centred on AR as the mediator for the interaction between the human and the robot, this category does not include cases such as when the robot gains perceptual information merely through external sensors. This category shall only be limited to when information is acquired through human interaction via AR. Mirroring the categorisation of augmented human perception, this group can be further sub-categorised to reflect the three main entities in an HRI task: the human, the robot and the environment. The purpose of AR as the mediator for the interaction is to augment the robot's perception of the human, the environment or the robot itself.

Augmented robot perception of the human: AR serves as an interface for the robot to gain information about the human. An example is [35] where HRI is enabled by integrating AR with a Brain-Computer Interface (BCI). To send commands to the robot, the human gazes on the desired flickering option shown in the AR display. The robot thereby receives perceptual data concerning the user via AR. The augmentation may also be used for acquiring deeper comprehension of the human. As an example, in [36], the robot infers the human's goals and actions by examining the human's gaze on AR objects. In [37], the robot infers the human's set of tasks for its arm to perform. If it registers any ambiguity or uncertainty, the human directs the robot towards the desired virtual trajectory shown in AR. Training of learning agents via AR is still a relatively new area. We propose that current robot training methods could be extended to incorporate AR. A human's interaction with virtual elements could for instance be used to help the robot form the user's mental model to estimate his/her preferences or decision-making.

Augmented robot perception of the environment: In this category, AR augments the robot's perception of the environment. An example is when human children draw lines with different coloured digital pens on the floor [38]. The colour that the robot is on top of is used to dictate the robot's behaviour. In [39], as the robot explores an unfamiliar area, it generates a virtual map visible to the human. The user is able to edit the robot's map and hence modify the robot's perception of the environment. Using projection-based AR, the authors in [40] were able to define regions of obstacles to the robot to supplement the robot's perception of its environment. In [41], the robot learns an assembly sequence from human demonstration by watching the virtual parts being assembled by the human. As the virtual objects are being moved around, the robot's perception of the environment is changed.

Augmented robot perception of self: Here, the user may interact with virtual objects to augment the robot's perceptual information regarding itself. For instance, the user may instruct a robot to move through a specified trajectory by dragging the virtual object to a goal location within the AR environment [42]. By recognising the interaction of the human with the virtual object, the robot is able to infer its current state in relation to its goal state. In [25], when the robot fails to open a different type of bottle using its existing knowledge, the human is able to correct the robot via feedback given through AR. This new information from the human therefore allows the robot to update its comprehension.

Although this taxonomy separates the different parts of perceptions being augmented, the augmentation could belong to several of the above categories simultaneously. For instance, Reardon et al. [43] use AR to indicate the areas that the human-robot team has visited in an exploration task. This information adds to a human's perception of the environment, of the robot and of her/himself. The visualisation of explored locations indicates to the user the parts of the environment that the team has investigated. It also conveys to the user what information the robot and the human have accumulated at that point in time.

IV. Classification of functional roles of AR in HRI

Although the classification in the previous section presents the different places of perceptual augmentation, it includes every minuscule interaction and hence does not describe the overall high-level function for the user. Hugues et al [4] proposed a functional taxonomy for AR which presents two main AR functionalities - one which adds a virtual environment not based on the current reality, and the other which aims to augment the understanding of the present. In this section, we extend this functional taxonomy of AR to highlight user-centred functional roles of AR within HRI.

A. Artificial Timescale

This category has been derived from the *Artificial Environment* functionality in [4]. It provides a virtual scene not based on the present reality. The authors also provided the notion that it is used to alter the timeline - by using it to imagine the future, have a glimpse into the past, or envision the impossibility.

In [44], the user is able to plan a welding process by adding waypoints for the robot's welding gun to follow. The system also allows the user to see if the robot *will* be able to reach the specified areas. In [45], the user is able to virtually fly the future version of the robot in real-time as the physical robot follows it. Also envisaging the future, Leutert et al. [46] enabled a robot's drawing to be visualised before the robot even began to draw.

A view into the past is exemplified in [47] where hovering over a specific robot on the AR display shows its debug message history. This logging information includes the detection of other robots in the past and the messages sent and received. In addition, AR has been used to illustrate what historical landmarks used to look like in the past [48]. Using a similar approach in robotics could provide the human a visualisation of the robot's history. For example, to understand the cause of an unsatisfactory outcome of a robot's behaviour, it may be beneficial for the human to be able to view the robot's past states.

An impossibility can also be imagined by rendering virtual scenes which may never exist. For example, in [49], projection-based AR was used to incorporate a virtual game environment into the real world for a human-robot collaborative sheep herding game. Qiu et al. [50] created a shared artificial world for the human and the robot to play a collection game. These virtual elements are not intended to represent scenarios which may occur in the future or did occur at one point in time; rather, they are used to imagine a reality that would never occur.

State space search is a common process used in artificial intelligence [51], [52]. This can also be applied to AR-for-HRI. The concept of alternate timelines revolves around the idea that there exists another reality which could have branched off from the present reality at some point in the past (Figure 3). It answers the question of *what could have happened?* Conveying this information to the user would, in effect, enable the alternate timeline. The alternate state in question could be the state of the robot, the state of the human, the state of the environment or a combination between the three.

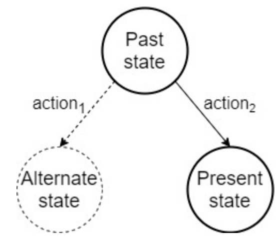

Fig. 3: A graphical representation of the alternate timeline: alternate reality is simply the new state that the past state would have transitioned to, had a different action been taken.

B. Augmented Comprehension of the Present Reality

As proposed by Hugues et al. [4], the other functionality of AR is to augment the understanding of the present reality. In this function, AR can be used to provide additional knowledge about the real environment or the state of the robot. For instance, in [53], in a human-robot collaborative car door assembly task, the AR technology allowed for objects hidden inside a toolbox to be visualised to the human collaborator. In [54], the penetration depth of the robot's drill in the workpiece is visualised to the user. In the form of perspective-taking, the robot's first person view (FPV) can be streamed to the user's AR device to allow the user to obtain the robot's FPV and third person view simultaneously [55]. This category represents a large part of HRI as it serves to inform the user about the situation at hand. This functionality can potentially be more effective than the traditional method of requiring a separate monitor screen to display virtual information. This reduces the need for context-switching between the screen and the view of the real scene. However, the effects of AR on context-switching and performance may still need to be assessed.

C. Augmented Control

Although the original classification in [4] represents possible functional roles of AR to the human user, it lacks the perspective of HRI. Williams et al. [5] introduced the concepts of *expressivity of view* and *flexibility of control* in virtual/augmented reality for HRI. We adopt and revise these two parameters to assess the functionality of AR. The two previous functionalities we proposed describe information the user obtains from AR, aligning with *expressivity of view*. Here we propose an additional functional role of AR in the context of HRI to portray *flexibility of control* in the functionality context: the ability for the user to control the robot. Currently, AR provides augmented control in different forms including

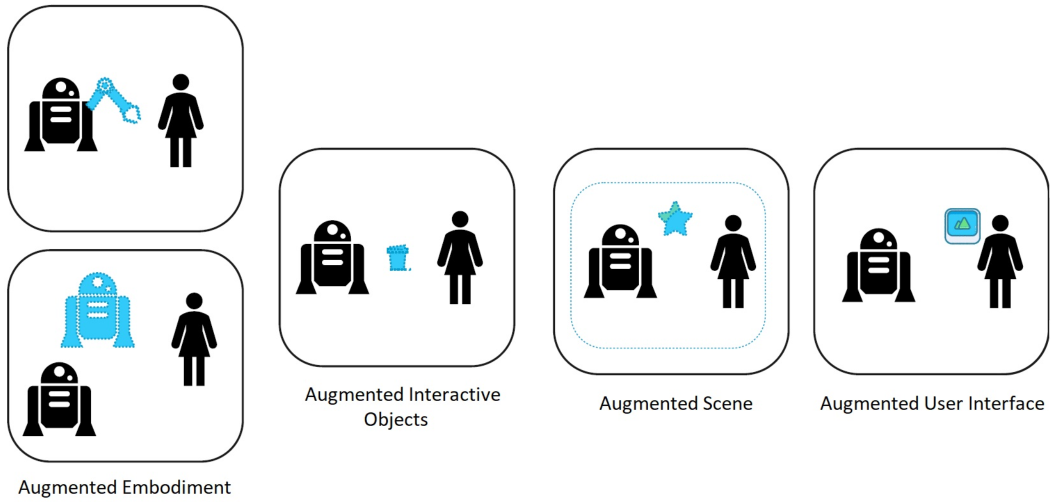

Fig. 4: Classification of the augmentation artifact types in HRI: a) Augmented Embodiment, where augmentation could be in the form of a robot arm or another robot, b) Augmented Interactive Objects are artifacts which the robot or human can interact with, c) Augmented Scene, where artifacts make up the scene, and d) Augmented User Interface, where artifacts are used to augment the user viewpoint

traditional menu buttons and interactive virtual objects in the robot's environment. In [56], users were able to control the robot by using tongue movements to select options in an AR menu. Providing augmented control in the form of virtual objects in the robot's environment, in [57], users were able to control a robot manipulation task by dragging virtual objects to desired locations. This provided a more intuitive and simple way of instructing the robot compared to teleoperating the robot using a traditional controller. Yonezawa and Ogawa [58] implemented a system where the user can draw on a virtual plane to control a flying robot, with its speed being dictated by the drawing speed. This gives novice users the ability to control the robot to perform complicated manoeuvres. In [59], a human is able to take a virtual block from a robot's work area to get it to re-plan the block assembly task without the need of said block. Since AR allows 3D interactions, it seems that AR controllers could potentially be more natural than other projected controllers. However, the usability and cognitive load resulting from these AR interfaces should be assessed.

V. Anchors and Types of AR-HRI Artifacts

In AR, virtual content is integrated into the real world in real time. Although this information can be in the form of hearing, touch or smell, current AR research largely revolves around visual approaches. Herein, virtual objects are presented to the user on the user's display to deliver information. These virtual objects, also referred to as *artifacts* in this taxonomy, can be in several forms such as texts, symbols or 2D/3D models.

Müller et al. [60] suggested that there are two reference systems for the positioning of the augmentation in AR: the world coordinate system (WCS) and the spectator coordinate system (SPC). The former refers to when the visual augmentation is *anchored* to a point in the real world. That is, the real world serves as the reference point for the virtual artifact. In the SPC, on the other hand, the visual augmentation is anchored to the user's viewpoint. Here, regardless of the movement of the user viewpoint, the visual augmentation remains in the same location with respect to the user viewpoint.

Including the context of robotics into the classification, [55] and [61] introduced a visual design framework for AR to categorise the three possible locations of visual augmentation:

- *User interface*: the augmented visuals are anchored directly to the user's view. Regardless of the location or direction of the user viewpoint, these virtual elements remain in the same place with respect to the user display.
- *Robot*: these virtual elements are anchored to the robot and hence move with the robot.
- *Environment*: the reference point of these AR visuals is neither the robot nor the user interface. Rather, they are embedded into the operational environment.

Building on this AR-HRI design framework, we present a classification of AR artifacts based on their functions (Figure 4):

- **Augmented Embodiment**, in which the artifact is placed: on the robot body (for instance, to increase its communication capabilities with social features [62]), on the human body (such as a virtual exoskeleton [63]), or as a whole new robot (in the context of swarm robots for instance [64]). The augmented embodiment is not necessarily anthropomorphic and could be used to render robot's internal status such as in [65] where the Thymio robot wears a shell that displays the status of its infrared sensors.

- **Augmented Interactive Objects** designates virtual objects placed in the real world which the human or robot could interact with. For example, Frank et al. [66] uses AR to render objects in the context of a manipulation task.
- **Augmented User Interface** refers to cases in which the virtual objects are fixed in place on the user display regardless of the orientation or location of the user viewpoint. For instance, the robot's camera view fixed on one side of the user display in [55] is an augmented user interface artifact.
- **Augmented Scene** refers to the remaining virtual objects which do not fit into any of the above categories. They do not act as a part of the robot, the human or the user interface, and they are non-interactive. Nevertheless, they contribute to present the scene on the AR display. An example is the robot's colored local costmap shown in AR to the user in [67] or the virtual colormap in [68] to help with depth perception during a manipulation task.

Although the classification from [55] and [61] contains robot-attachment as a category, for the artifact type, we have adopted and modified the class to Augmented Embodiment to reflect the virtual artifacts which serve as a part of the body of the robot or the human. The aforementioned interface design framework also includes a category for the virtual objects embedded in the environment. However, we wanted to distinguish between the types of these objects in terms of interactivity as *a)* AR heavily revolves around interactivity [1], and *b)* interactivity is a core part of human-robot interaction.

VI. Demonstration of the Taxonomy

While a full literature review of AR-for-HRI is beyond the scope of this paper, in this section we demonstrate how recent HRI studies can be placed in our multidimensional taxonomy. We categorise the 20 most cited publications in AR-for-HRI between the years of 2011-2021.

A. Acquisition of Publications

To retrieve relevant publications to demonstrate our taxonomy, in September 2021 we conducted a search in the electronic database Scopus using the following search strategy:

We conducted a keyword search in the publication title and the abstract for the years 2011-2021 containing "augmented reality" AND "human-robot interaction". Duplicates were removed and papers selected according to the following criteria:

- The paper contains a study involving the interaction between a human and a physical robot through an augmented reality application

Papers were excluded if they met the following criteria:

- Augmented reality is not involved in the interface between the human and the robot
- The paper only provides a summary of other AR-for-HRI studies
- The paper is conceptual with no implementation

After ordering the publications based on their number of citations (extracted from Scopus), we kept for analysis the 20 most cited paper that were not duplicates and respected the above eligibility criteria.

B. Classification of Publications

The 20 publications obtained were classified based on 1) the perception augmentation type, 2) the AR functional role, and 3) the augmentation artifact type. For each paper, the categories were recorded and are presented in Table I. As shown, all 20 studies fall under all three subcategories of augmented human perception. This suggests that high importance is placed on the augmentation of human perception. This is as expected as AR technologies are primarily used to aid the human experience. The range of human perception augmentations therefore tends to be more well-researched than that of the robot. It is, however, important to note that the category of augmented robot perception in this paper is reserved for augmentations via AR interactions. Hence, this table does not represent the full breadth of human-to-robot information transfer in these publications.

The AR functional roles amongst the papers were evenly split for Artificial Timescale and Augmented Comprehension. All but three studies utilised the Augmented Control functionality, suggesting that AR is a recognised mediator for robot control. In regards to the virtual artifact classification, every paper contained at least one of the proposed artifact types. The number of artifact types employed ranges from one to four. To further analyse the patterns, a larger sample of publications would be favourable.

Although the number of papers examined here is not exhaustive, the table suggests that there could currently be a gap in the most cited research for the robot's side of perception in AR-for-HRI.

VII. Discussion and Opportunities

AR has a great potential to mediate human-robot interaction by bridging the digital and physical worlds in which the robot operates. Several crucial challenges in HRI such as trust, safety and explainability could find in AR ways to embed visualisation that could allow better understanding from the user's point of view. For instance, safe areas and shared workspaces could be displayed for the user's safety in a physical HRI scenario [78] [82]; and augmented temporality could be used to allow better explainabilty in autonomous decision making systems.

There are many different aspects to AR in HRI. With this work, we proposed a focus scope of categories around the functional role of AR in HRI and several complementary taxonomies were presented in the literature [5], [55], [60], [61]. While demonstrating the use of our taxonomy on a sample of the state-of-the-art, we observe many of the proposed categorisations are useful to distinguish the different works. We also found some potential research directions for AR specific to the HRI context:

Although augmented human perception is widely employed in AR-for-HRI, it may be insightful to examine how augmented perception is used. For instance, the augmentation

TABLE I: Demonstration of how the top 20 cited publications are placed within the taxonomy. Each paper was categorised by 1) augmented perception, 2) AR functional role and 3) augmentation artifact type

Article	Augmented Perception: Human	Augmented Perception: Robot	Function	Artifact
	Self, Environment, Robot	Self, Environment, Human	Augmented Control, Augmented Comprehension, Artificial Timescale	Augmented UI, Augmented Scene, Augmented Interactive Objects, Augmented Embodiment
[69]	●●●	●●●	●○●	●●○○
[61]	●●●	●○○	●●●	●○●●
[55]	●●●	○○○	○●○	○○●●
[70]	●●●	●○○	○●●	○●●●
[71]	●●●	●●●	●○●	●●○○
[72]	●●●	○○○	○●○	●●●●
[49]	●●●	●●○	●○●	●●●○
[46]	●●●	●●○	●○●	●●●○
[73]	●●●	●●●	●○●	○●○○
[74]	●●●	●●●	○●●	○●●●
[75]	●●●	●●●	○●●	○○●●
[76]	●●●	●●●	●○●	●●○○
[66]	●●●	●●●	●○●	○●○●
[42]	●●●	●●●	●●●	○●○○
[45]	●●●	●●●	●●●	●●●○
[77]	●●●	●○○	○●●	○○●○
[78]	●●●	○○○	○●○	○○●●
[79]	●●●	●●●	○●●	●●●○
[80]	●●●	●●●	●○●	○●○○
[81]	●●●	●●●	●●●	○●○○

●=Yes; ○=No.

of robot perception via AR could be further investigated to improve robot learning. With ongoing research in human-in-the-loop learning agents [83], [84], bringing AR into the field could be advantageous as it expands interaction capabilities. Using human input via AR may aid the robot's understanding of the environment since *a)* capabilities of external sensors may be limited, *b)* AR merges the virtual and physical worlds, homogenizing the languages of the human and the robot, and *c)* via AR, the user can now directly communicate his/her preferences.

To our knowledge, the use of AR to create an alternative reality view, or a view into the past to aid our comprehension of the agent's mental model, has not been explored. For future research, it may be insightful to investigate if there is a link between the functional role of AR and the robot's task.

For the same function, AR can take many forms. However the design of these artifacts can be crucial in terms of usability and efficiency for the user [55]. Similarly to the AR functional role, future work could explore the relationship between the artifact type and the task of the robot. It will also be beneficial to have a quantitative method for measuring the utility of these artifacts based on their functions. With our proposed categories, we hope to help future research describe the functional roles of AR as well as the artifacts used to achieve these functions.

VIII. Conclusion

In this paper, we gave an overview of current HRI styles, including how AR comes into play. We introduced three new dimensions to the AR-for-HRI classification system: perception augmentation, functional role of AR and augmentation artifact type. Lastly, we demonstrated how the 20 most cited AR-for-HRI publications can be classed using our taxonomy.

Similarly to what was done for data visualisation [85], user experiments could help to assess the potential combination between: *1)* the type of augmented perception *(what)*, *2)* the function of AR *(why)*, and *3)* the type of artifacts *(how)* in order to build an AR visual grammar for HRI. In that sense, our taxonomy is currently limited as it does not evaluate the efficiency of the various AR-for-HRI designs and scenarios. However, using our taxonomy, we hope that the reader will find inspiration to explore various functional scenarios and gather empirical research evidence that will allow the design of such grammar of AR-for-HRI.

References

[1] R. Azuma, Y. Baillot, R. Behringer, S. Feiner, S. Julier, and B. MacIntyre, "Recent advances in augmented reality," *IEEE Computer Graphics and Applications*, vol. 21, no. 6, pp. 34–47, Nov. 2001, conference Name: IEEE Computer Graphics and Applications.

[2] Z. Makhataeva and H. A. Varol, "Augmented Reality for Robotics: A Review," *Robotics*, vol. 9, no. 2, p. 21, Jun. 2020.

[3] P. Milgram and H. Colquhoun, "A Taxonomy of Real and Virtual World Display Integration," Jan. 2001.

[4] O. Hugues, P. Fuchs, and O. Nannipieri, "New augmented reality taxonomy: Technologies and features of augmented environment," in *Handbook of augmented reality*. Springer, 2011, pp. 47–63.

[5] T. Williams, D. Szafir, and T. Chakraborti, *The Reality-Virtuality Interaction Cube*, Mar. 2020.

[6] J. Rekimoto and K. Nagao, "The world through the computer: Computer augmented interaction with real world environments," in *Proceedings of the 8th annual ACM symposium on User interface and software technology*, 1995, pp. 29–36.

[7] K. B. Reed, M. Peshkin, M. J. Hartmann, J. E. Colgate, and J. Patton, "Kinesthetic interaction," in *9th International Conference on Rehabilitation Robotics, 2005. ICORR 2005.* IEEE, 2005, pp. 569–574.

[8] A. Özgür, S. Lemaignan, W. Johal, M. Beltran, M. Briod, L. Pereyre, F. Mondada, and P. Dillenbourg, "Cellulo: Versatile handheld robots for education," in *2017 12th ACM/IEEE International Conference on Human-Robot Interaction (HRI.* IEEE, 2017, pp. 119–127.

[9] Y. Gao, S. Wallkötter, M. Obaid, and G. Castellano, "Investigating deep learning approaches for human-robot proxemics," in *2018 27th IEEE International Symposium on Robot and Human Interactive Communication (RO-MAN)*, 2018, pp. 1093–1098.

[10] T. Kosiński, M. Obaid, P. W. Woźniak, M. Fjeld, and J. Kucharski, "A fuzzy data-based model for human-robot proxemics," in *2016 25th IEEE International Symposium on Robot and Human Interactive Communication (RO-MAN)*, 2016, pp. 335–340.

[11] B. Akgun, M. Cakmak, J. W. Yoo, and A. L. Thomaz, "Trajectories and keyframes for kinesthetic teaching: A human-robot interaction perspective," in *Proceedings of the seventh annual ACM/IEEE international conference on Human-Robot Interaction*, 2012, pp. 391–398.

[12] S. Serholt, C. A. Basedow, W. Barendregt, and M. Obaid, "Comparing a humanoid tutor to a human tutor delivering an instructional task to children," in *2014 IEEE-RAS International Conference on Humanoid Robots*, 2014, pp. 1134–1141.

[13] W. Johal, "Research trends in social robots for learning," *Current Robotics Reports*, pp. 1–9, 2020.

[14] A. Tang, C. Owen, F. Biocca, and W. Mou, "Comparative effectiveness of augmented reality in object assembly," in *Proceedings of the SIGCHI conference on Human factors in computing systems*, 2003, pp. 73–80.

[15] D. J. Rea and J. E. Young, "It's all in your head: Using priming to shape an operator's perceptions and behavior during teleoperation," in *Proceedings of the 2018 ACM/IEEE International Conference on Human-Robot Interaction*, ser. HRI '18. New York, NY, USA: Association for Computing Machinery, 2018, p. 32–40.

[16] C. Passenberg, A. Peer, and M. Buss, "A survey of environment-, operator-, and task-adapted controllers for teleoperation systems," *Mechatronics*, vol. 20, no. 7, pp. 787–801, 2010.

[17] P. Simoens, M. Dragone, and A. Saffiotti, "The internet of robotic things: A review of concept, added value and applications," *International Journal of Advanced Robotic Systems*, vol. 15, no. 1, p. 1729881418759424, 2018.

[18] M. Lewis, J. Wang, and S. Hughes, "Usarsim: Simulation for the study of human-robot interaction," *Journal of Cognitive Engineering and Decision Making*, vol. 1, no. 1, pp. 98–120, 2007.

[19] E. Pairet, P. Ardon, X. Liu, J. Lopes, H. Hastie, and K. S. Lohan, "A digital twin for human-robot interaction," in *2019 14th ACM/IEEE International Conference on Human-Robot Interaction (HRI)*, 2019, pp. 372–372.

[20] O. Liu, D. Rakita, B. Mutlu, and M. Gleicher, "Understanding human-robot interaction in virtual reality," in *2017 26th IEEE International Symposium on Robot and Human Interactive Communication (RO-MAN)*. IEEE, 2017, pp. 751–757.

[21] R. Li, M. van Almkerk, S. van Waveren, E. Carter, and I. Leite, "Comparing human-robot proxemics between virtual reality and the real world," in *2019 14th ACM/IEEE International Conference on Human-Robot Interaction (HRI)*, 2019, pp. 431–439.

[22] D. Szafir, "Mediating human-robot interactions with virtual, augmented, and mixed reality," in *International Conference on Human-Computer Interaction*. Springer, 2019, pp. 124–149.

[23] P. B. Sydhagen, "How can we distinguish perception from cognition? the perceptual adaptation hypothesis," Master's thesis, 2017.

[24] R. L. Goldstone and L. W. Barsalou, "Reuniting perception and conception," *Cognition*, vol. 65, no. 2, pp. 231–262, Jan. 1998. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0010027797000474

[25] H. Liu, Y. Zhang, W. Si, X. Xie, Y. Zhu, and S.-C. Zhu, "Interactive Robot Knowledge Patching Using Augmented Reality," in *2018 IEEE International Conference on Robotics and Automation (ICRA)*, May 2018, pp. 1947–1954.

[26] M. Zolotas, J. Elsdon, and Y. Demiris, "Head-Mounted Augmented Reality for Explainable Robotic Wheelchair Assistance," in *2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, Oct. 2018, pp. 1823–1829.

[27] C. Papachristos and K. Alexis, "Augmented reality-enhanced structural inspection using aerial robots," in *2016 IEEE International Symposium on Intelligent Control (ISIC)*, Sep. 2016, pp. 1–6.

[28] T. Groechel, Z. Shi, R. Pakkar, and M. J. Matarić, "Using Socially Expressive Mixed Reality Arms for Enhancing Low-Expressivity Robots," in *2019 28th IEEE International Conference on Robot and Human Interactive Communication (RO-MAN)*, Oct. 2019, pp. 1–8.

[29] T. Sawabe, S. Honda, Y. Fujimoto, M. Kanbara, and H. Kato, "Investigation of the Human-Robot Interaction in Affective Robotics Using HRI with apparent differences in VR/AR," 2020.

[30] C. Reardon, J. Gregory, C. Nieto-Granda, and J. G. Rogers, "Enabling Situational Awareness via Augmented Reality of Autonomous Robot-Based Environmental Change Detection," in *International Conference on Human-Computer Interaction*, J. Y. C. Chen and G. Fragomeni, Eds. Springer, 2020, pp. 611–628.

[31] N. Tran, T. Grant, T. Phung, L. Hirshfield, C. Wickens, and T. Williams, "Get This!? Mixed Reality Improves Robot Communication Regardless of Mental Workload," in *Companion of the 2021 ACM/IEEE International Conference on Human-Robot Interaction*, Mar. 2021, pp. 412–416.

[32] M. Chen, P. Zhang, Z. Wu, and X. Chen, "A multichannel human-swarm robot interaction system in augmented reality," *Virtual Reality & Intelligent Hardware*, vol. 2, no. 6, pp. 518–533, Dec. 2020.

[33] H. Peng, J. Briggs, C.-Y. Wang, K. Guo, J. Kider, S. Mueller, P. Baudisch, and F. Guimbretière, "RoMA: Interactive Fabrication with Augmented Reality and a Robotic 3D Printer," in *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*, Apr. 2018, pp. 1–12.

[34] M. Krüger, M. Weigel, and M. Gienger, "Visuo-tactile AR for Enhanced Safety Awareness in Human-Robot Interaction."

[35] X. Chen, X. Huang, Y. Wang, and X. Gao, "Combination of Augmented Reality Based Brain- Computer Interface and Computer Vision for High-Level Control of a Robotic Arm," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 28, no. 12, pp. 3140–3147, Dec. 2020.

[36] D. Puljiz, B. Zhou, K. Ma, and B. Hein, "HAIR: Head-mounted AR Intention Recognition," *arXiv preprint arXiv:2102.11162*, Feb. 2021.

[37] J. F. Mullen, J. Mosier, S. Chakrabarti, A. Chen, T. White, and D. P. Losey, "Communicating Inferred Goals With Passive Augmented Reality and Active Haptic Feedback," *IEEE Robotics and Automation Letters*, Oct. 2021.

[38] R. Wistort and C. Breazeal, "TofuDraw: a mixed-reality choreography tool for authoring robot character performance," in *Proceedings of the 10th International Conference on Interaction Design and Children*, ser. IDC '11, Jun. 2011, pp. 213–216.

[39] A. Sidaoui, I. H. Elhajj, and D. Asmar, "Collaborative Human Augmented SLAM," in *2019 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, Nov. 2019, pp. 2131–2138.

[40] A. Gaschler, M. Springer, M. Rickert, and A. Knoll, "Intuitive robot tasks with augmented reality and virtual obstacles," in *2014 IEEE International Conference on Robotics and Automation (ICRA)*, May 2014, pp. 6026–6031.

[41] W. Zou, M. Andulkar, and U. Berger, "Development of Robot Programming System through the use of Augmented Reality for Assembly Tasks," in *ISR 2018; 50th International Symposium on Robotics*, Jun. 2018, pp. 1–7.

[42] S. Blankemeyer, R. Wiemann, L. Posniak, C. Pregizer, and A. Raatz, "Intuitive Robot Programming Using Augmented Reality," *Procedia CIRP*, vol. 76, pp. 155–160, Jan. 2018.

[43] C. Reardon, K. Lee, J. G. Rogers, and J. Fink, "Communicating via Augmented Reality for Human-Robot Teaming in Field Environments," in *2019 IEEE International Symposium on Safety, Security, and Rescue Robotics (SSRR)*, Sep. 2019, pp. 94–101.

[44] S. K. Ong, A. Y. C. Nee, A. W. W. Yew, and N. K. Thanigaivel, "AR-assisted robot welding programming," *Advances in Manufacturing*, vol. 8, no. 1, pp. 40–48, Mar. 2020.

[45] M. E. Walker, H. Hedayati, and D. Szafir, "Robot Teleoperation with Augmented Reality Virtual Surrogates," in *2019 14th ACM/IEEE International Conference on Human-Robot Interaction (HRI)*, Mar. 2019, pp. 202–210.

[46] F. Leutert, C. Herrmann, and K. Schilling, "A Spatial Augmented Reality system for intuitive display of robotic data," Mar. 2013, pp. 179–180.

[47] F. Ghiringhelli, J. Guzzi, G. A. Di Caro, V. Caglioti, L. M. Gambardella, and A. Giusti, "Interactive Augmented Reality for understanding and analyzing multi-robot systems," in *2014 IEEE/RSJ International Conference on Intelligent Robots and Systems*, Sep. 2014, pp. 1195–1201.

[48] M. Duguleana, R. Brodi, F. Girbacia, C. Postelnicu, O. Machidon, and M. Carrozzino, "Time-travelling with mobile augmented reality: A case study on the piazza dei miracoli," in *Euro-Mediterranean Conference*. Springer, 2016, pp. 902–912.

[49] A. S. Clair and M. Matarić, "How Robot Verbal Feedback Can Improve Team Performance in Human-Robot Task Collaborations," in *2015 10th ACM/IEEE International Conference on Human-Robot Interaction (HRI)*, Mar. 2015, pp. 213–220.

[50] S. Qiu, H. Liu, Z. Zhang, Y. Zhu, and S.-C. Zhu, "Human-Robot Interaction in a Shared Augmented Reality Workspace," in *2020 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, Oct. 2020, pp. 11 413–11 418.

[51] W. Zhang, *State-space search: Algorithms, complexity, extensions, and applications*. Springer Science & Business Media, 1999.

[52] L. Kanal and V. Kumar, *Search in artificial intelligence*. Springer Science & Business Media, 2012.

[53] R. Kalpagam Ganesan, Y. K. Rathore, H. M. Ross, and H. Ben Amor, "Better Teaming Through Visual Cues: How Projecting Imagery in a Workspace Can Improve Human-Robot Collaboration," *IEEE Robotics Automation Magazine*, vol. 25, no. 2, pp. 59–71, Jun. 2018, conference Name: IEEE Robotics Automation Magazine.

[54] D. Sirintuna, Y. Aydin, O. Caldiran, O. Tokatli, V. Patoglu, and C. Basdogan, "A Variable-Fractional Order Admittance Controller for pHRI," in *2020 IEEE International Conference on Robotics and Automation (ICRA)*, May 2020, pp. 10 162–10 168.

[55] H. Hedayati, M. Walker, and D. Szafir, "Improving Collocated Robot Teleoperation with Augmented Reality," in *2018 13th ACM/IEEE Inter-*

national Conference on Human-Robot Interaction (HRI), Mar. 2018, pp. 78–86.

[56] F.-J. Chu, R. Xu, Z. Zhang, P. A. Vela, and M. Ghovanloo, "Hands-Free Assistive Manipulator Using Augmented Reality and Tongue Drive System," in *2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, Oct. 2018, pp. 5463–5468.

[57] A. Dias, H. Wellaboda, Y. Rasanka, M. Munasinghe, R. Rodrigo, and P. Jayasekara, "Deep Learning of Augmented Reality based Human Interactions for Automating a Robot Team," in *2020 6th International Conference on Control, Automation and Robotics (ICCAR)*, Apr. 2020, pp. 175–182.

[58] K. Yonezawa and T. Ogawa, "Flying robot manipulation system using a virtual plane," in *2015 IEEE Virtual Reality (VR)*, Mar. 2015, pp. 313–314.

[59] T. Chakraborti, S. Sreedharan, A. Kulkarni, and S. Kambhampati, "Alternative Modes of Interaction in Proximal Human-in-the-Loop Operation of Robots," Mar. 2017.

[60] T. Müller and R. Dauenhauer, "A taxonomy for information linking in augmented reality," in *International Conference on Augmented Reality, Virtual Reality and Computer Graphics*. Springer, 2016, pp. 368–387.

[61] M. Walker, H. Hedayati, J. Lee, and D. Szafir, "Communicating Robot Motion Intent with Augmented Reality," in *Proceedings of the 2018 ACM/IEEE International Conference on Human-Robot Interaction*, Feb. 2018, pp. 316–324.

[62] J. Hamilton, N. Tran, and T. Williams, "Tradeoffs Between Effectiveness and Social Perception When Using Mixed Reality to Supplement Gesturally Limited Robots," in *International Workshop on Virtual, Augmented, and Mixed Reality for Human-Robot Interaction*, vol. 3, Mar. 2020.

[63] M. Meng, P. Fallavollita, T. Blum, U. Eck, C. Sandor, S. Weidert, J. Waschke, and N. Navab, "Kinect for interactive AR anatomy learning," in *2013 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*, Oct. 2013, pp. 277–278.

[64] V. Edwards, P. Gaskell, and E. Olson, "Calibrating Mixed Reality for Scalable Multi-Robot Experiments," in *Proceedings of the 17th International Conference on Autonomous Agents and MultiAgent Systems*, ser. AAMAS '18. Richland, SC: International Foundation for Autonomous Agents and Multiagent Systems, Jul. 2018, pp. 2183–2185.

[65] W. Johal, O. Robu, A. Dame, S. Magnenat, and F. Mondada, "Augmented robotics for learners: A case study on optics," in *2019 28th IEEE International Conference on Robot and Human Interactive Communication (RO-MAN)*. IEEE, 2019, pp. 1–6.

[66] J. A. Frank, M. Moorhead, and V. Kapila, "Realizing mixed-reality environments with tablets for intuitive human-robot collaboration for object manipulation tasks," in *2016 25th IEEE International Symposium on Robot and Human Interactive Communication (RO-MAN)*, Aug. 2016, pp. 302–307.

[67] F. Muhammad, A. Hassan, A. Cleaver, and J. Sinapov, "Creating a shared reality with robots," in *Proceedings of the 14th ACM/IEEE International Conference on Human-Robot Interaction*, ser. HRI '19. Daegu, Republic of Korea: IEEE Press, Mar. 2019, pp. 614–615.

[68] S. Arevalo Arboleda, F. Rücker, T. Dierks, and J. Gerken, "Assisting Manipulation and Grasping in Robot Teleoperation with Augmented Reality Visual Cues," in *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*. Yokohama Japan: ACM, May 2021, pp. 1–14.

[69] H. C. Fang, S. K. Ong, and A. Y. C. Nee, "Interactive robot trajectory planning and simulation using Augmented Reality," *Robotics and Computer-Integrated Manufacturing*, vol. 28, no. 2, pp. 227–237, Apr. 2012.

[70] G. Michalos, N. Kousi, P. Karagiannis, C. Gkournelos, K. Dimoulas, S. Koukas, K. Mparis, A. Papavasileiou, and S. Makris, "Seamless human robot collaborative assembly – An automotive case study," *Mechatronics*, vol. 55, pp. 194–211, Nov. 2018.

[71] S. Ong, A. Yew, N. Thanigaivel, and A. Nee, "Augmented reality-assisted robot programming system for industrial applications," *Robotics and Computer-Integrated Manufacturing*, vol. 61, p. 101820, Feb. 2020.

[72] F. Brizzi, L. Peppoloni, A. Graziano, E. D. Stefano, C. A. Avizzano, and E. Ruffaldi, "Effects of Augmented Reality on the Performance of Teleoperated Industrial Assembly Tasks in a Robotic Embodiment," *IEEE Transactions on Human-Machine Systems*, vol. 48, no. 2, pp. 197–206, Apr. 2018, conference Name: IEEE Transactions on Human-Machine Systems.

[73] J. Lambrecht and J. Krüger, "Spatial programming for industrial robots based on gestures and Augmented Reality," in *2012 IEEE/RSJ International Conference on Intelligent Robots and Systems*, Oct. 2012, pp. 466–472.

[74] A. Hietanen, R. Pieters, M. Lanz, J. Latokartano, and J.-K. Kämäräinen, "AR-based interaction for human-robot collaborative manufacturing," *Robotics and Computer-Integrated Manufacturing*, vol. 63, p. 101891, Jun. 2020.

[75] H. Zeng, Y. Wang, C. Wu, A. Song, J. Liu, P. Ji, B. Xu, L. Zhu, H. Li, and P. Wen, "Closed-Loop Hybrid Gaze Brain-Machine Interface Based Robotic Arm Control with Augmented Reality Feedback," *Frontiers in Neurorobotics*, vol. 11, p. 60, Oct. 2017.

[76] D. Ni, A. W. W. Yew, S. K. Ong, and A. Y. C. Nee, "Haptic and visual augmented reality interface for programming welding robots," *Advances in Manufacturing*, vol. 5, no. 3, pp. 191–198, Sep. 2017.

[77] V. Alvarez-Santos, R. Iglesias, X. M. Pardo, C. V. Regueiro, and A. Canedo-Rodriguez, "Gesture-based interaction with voice feedback for a tour-guide robot," *Journal of Visual Communication and Image Representation*, vol. 25, no. 2, pp. 499–509, Feb. 2014.

[78] S. Papanastasiou, N. Kousi, P. Karagiannis, C. Gkournelos, A. Papavasileiou, K. Dimoulas, K. Baris, S. Koukas, G. Michalos, and S. Makris, "Towards seamless human robot collaboration: integrating multimodal interaction," *The International Journal of Advanced Manufacturing Technology*, vol. 105, no. 9, pp. 3881–3897, Dec. 2019.

[79] A. Yew, S. Ong, and A. Nee, "Immersive Augmented Reality Environment for the Teleoperation of Maintenance Robots," *Procedia CIRP*, vol. 61, pp. 305–310, 2017.

[80] R. S. Andersen, S. Bøgh, T. B. Moeslund, and O. Madsen, "Intuitive task programming of stud welding robots for ship construction," in *2015 IEEE International Conference on Industrial Technology (ICIT)*, Mar. 2015, pp. 3302–3307.

[81] N. Li, S. Cartwright, A. Shekhar Nittala, E. Sharlin, and M. Costa Sousa, "Flying Frustum: A Spatial Interface for Enhancing Human-UAV Awareness," in *Proceedings of the 3rd International Conference on Human-Agent Interaction*, ser. HAI '15, Oct. 2015, pp. 27–31.

[82] Z. Makhataeva, A. Zhakatayev, and H. A. Varol, "Safety Aura Visualization for Variable Impedance Actuated Robots," in *2019 IEEE/SICE International Symposium on System Integration (SII)*, Jan. 2019, pp. 805–810.

[83] S. Chernova and A. L. Thomaz, "Robot Learning from Human Teachers," *Synthesis Lectures on Artificial Intelligence and Machine Learning*, vol. 8, no. 3, pp. 1–121, Apr. 2014.

[84] O. Kroemer, S. Niekum, and G. Konidaris, "A Review of Robot Learning for Manipulation: Challenges, Representations, and Algorithms," p. 82, 2021.

[85] T. Munzner, *Visualization analysis and design*. CRC press, 2014.