Using Augmented Reality to Better Study Human-Robot Interaction

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Abstract. In the field of Human-Robot Interaction, researchers often techniques such as the Wizard-of-Oz paradigms in order to better study narrow scientific questions while carefully controlling robots' capabilities unrelated to those questions, especially when those other capabilities are not yet easy to automate. However, those techniques often impose limitations on the type of collaborative tasks that can be used, and the perceived realism of those tasks and the task context. In this paper, we discuss how Augmented Reality can be used to address these concerns while increasing researchers' level of experimental control, and discuss both advantages and disadvantages of this approach.

Keywords: Human-Robot Interaction; Augmented Reality; Research Methods

1 Introduction

One of the greatest challenges in the development of interactive robots is the enabling of autonomous natural language capabilities [1]. Natural language understanding and generation are in general difficult problems to study due to the flexibility, ambiguity, and compositionality of natural language – the very reasons that make natural language such a powerful communication modality in the first place. But natural language interaction is *particularly* difficult to study within the context of human-robot interaction. While traditional natural language processing methods may be evaluated on text corpora, natural language communication in human-robot interaction is necessarily situated [2], with incredible sensitivity to that situated context [3, 4], and is almost entirely formulated as task-based dialogues [5], creating a need for situated, task-based study and evaluation of proposed and developed natural language architectures [6, 7].

Unfortunately, task-based evaluations themselves come with a host of challenges. In order for a task-based evaluation to be meaningful, it must allow for

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joint action [8] – communication and coordination of actions that change the state of human and robot teammates' shared context [9]. This in turn necessarily requires both parties to be able to *perceive* their shared environment, and for both parties to be able to take actions that *manipulate* their shared environment. Due to the difficulty of robot perception and action, human-robot experiments are often conducted through a *Wizard-of-Oz paradigm* [10–12] in which some or all of the robot's perception, cognition, or action is remotely dictated by an unseen human confederate, in theory allowing for study of interaction patterns before all technical challenges needed to truly enable such interactions are fully addressed.

Unfortunately, even Wizard-of-Ozing robot perception and action can be extremely challenging. Because there is no straightforward way of "telling" a robot what it sees and where it sees it, simplifying approaches to robot perception are typically needed, in one of two forms. First, the positions and properties of objects in the environment may be hard-coded a priori [13]. This allows a realistic interaction context to be presented to human participants that would look no different if the robot's perception were truly autonomous. However, it may preclude the possibility for collaborative interaction tasks involving joint action, as the objects in the environment cannot be manipulated without changing their (not truly observable) pose. On the other hand, objects in the scene may be augmented on all sides with fiducial markers [14, 15]; an approach that allows for fully manipulable and perceivable task contexts, but which necessarily changes the *human's* perception of their environment, such that it no longer truly looks as it would if the robot had full perceptual capabilities, and moreover such that human perception of task-relevant objects may in fact be impaired.

Similarly, Wizard-of-Ozing of robot motion also presents a significant challenge. Wizard-of-Ozing of actions in human-robot interaction typically involves human teleoperators manually selecting dialogue actions [16, 17], hard-coded physical actions like gestures [18,19], or full-body motions like traveling or turning [20,21]. As with wizarding approaches to robot perception, these approaches present interaction contexts to human participants that would look no different if the robot's actions were truly autonomous, but which may preclude the possibility for collaborative interaction task involving joint action, due to the difficulty of Wizarding within this framework the dextrous manipulation actions like grasping, picking, and placing that are necessary for truly collaborative tasks.

To address these problems, some researchers have begun to move the human-robot interaction *context* into a virtual domain, such as Lemaignan et al.'s *Free-play Sandbox* [22], Paiva et al.'s work within the EMOTE project [23,24] and in the context of the game *Sueca* [25], Kory and Breazel's storytelling work with Dragonbot [26], and Ramachandran and Scassellati's work on intelligent robot tutors [27]. In these approaches, humans and robots collaborate with respect to some task on a tablet computer. By moving the task into a virtual domain, this technique allows a robot to be fully autonomous without any perceptual or dexterous manipulation capabilities; a robot may instead directly access and manipulate the state of the collaborative task context by interfacing with the tablet responsible for displaying that context. However, this approach may also limit the perceived capability or agency of the robot teammate, due to such robots' real lack of capability and agency outside of the virtual domain. Moreover, working within this approach may limit the extensibility of researchers' work, in that advances in manipulation and perception will not clearly provide an opportunity to move the robot's operation from its virtual task context out to a more realistic, physically situated domain.

We argue that many of these challenges may be addressed using Augmented Reality technologies, by moving task-relevant objects from the physical world into the virtual world. Consider, for example, the game of *Sueca*, used as a task context by Correia et al. [25]. In order to study human-robot collaboration, the card game is played on an electronic tabletop, using a mixture of physical cards (played by humans) and virtual cards (played by the robot), with the physical cards instrumented with fiducial markers. There are at least three limitations of this approach. First, the authors report that this instrumentation was found to be jarring by participants. Second, this arrangement subtly treats human and robots players differently. Finally, this instrumentation may only really be feasible for certain types of games. In contrast, if players were instrumented with augmented reality headsets, each player *and robot* could manage a hand of virtual cards, addressing all of the concerns and challenges listed above while only minimally changing the appearance and interaction style from that of a normal game.

2 Case Study: Using Augmented Reality to Study the Use of Augmented Reality in Human-Robot Interaction

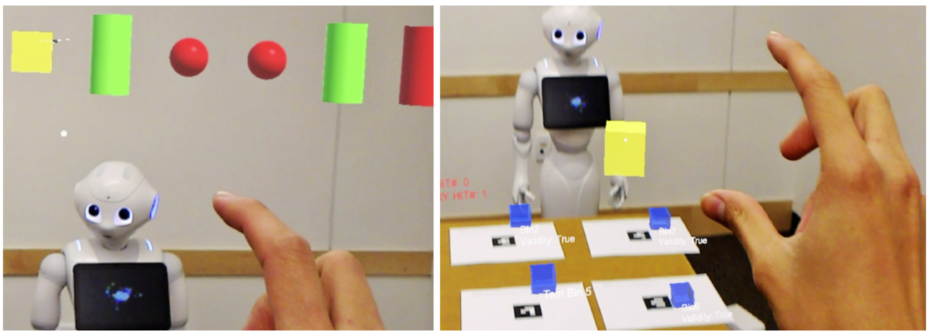

Fig. 1: Experiment in progress.

In this section, we present a case study of how AR might be used to improve the study of human-robot interaction. In fact, this case study will examine how we are using augmented reality objects to more easily study the general use of augmented reality in human-robot communication. In recent theoretical and experimental work, we have been exploring the space of possible robot gestures in human-robot interaction, including both physical gestures, and AR visualizations that may serve the same role as those gestures for armless robots or in privacy-sensitive applications [28]. Recently, for example, we have investigated the benefits of one particular type of augmented reality gesture, *allocentric gesture*, through online experiments in which participants watched videos in which simulated views of such gestures were displayed [29,30]. In our present work, we are now beginning to explore the effectiveness of this form of gesture in the real world using the Microsoft Hololens, in order to further interrogate our previously suggested hypotheses [31] regarding how these gestures may be differentially effective in the context of human-robot interactions under different mental workload conditions. Our main research question in this work is whether different types of human-robot communication (allocentric augmented reality gesture in the form of 3D arrows pointing to targets, and/or rich natural language) are more effective under different types of mental workload (working memory load, visual perceptual load, and auditory perceptual load). While this is experiment directly revolves around Augmented Reality, we are actually using Augmented Reality in supplemental ways not related to our core research questions in order to facilitate the research itself. Specifically, within this experiment, there are two different types of objects that are relevant to the task: **blocks** that the user must **pick**, and **bins** into which the user must **place** those blocks. This is a simple task in which the robot's job is purely communicative; it must periodically refer to different blocks, through either language or gesture. Accordingly, at least as described thus far, this is a task that could be easily implemented using physical bins and physical blocks, potentially with fiducial markers attached to the blocks so that the robot could easily determine where to visualize AR gestures with respect to those blocks. In our case, however, we decided to use an entirely virtual set of task objects (boxes and bins), because it allowed us to reap a number of benefits, alluded to above and thoroughly detailed in the following sections.

2.1 Advantages

No Need for Object Recognition

By using virtual objects, we obviate the need for object recognition in our experiments; because the robot used in our experiment (the Softbank Pepper) is directly interfaced with the Hololens, these task-relevant objects effectively live within the robot's world rather than the human's. Accordingly, the robot has oracle knowledge of the position of all bins without any sort of object recognition *and* without hardcoding the positions of those task-relevant objects. This drastically improves the consistency of interaction within the experiment; traditional object recognition is prone to errors in detection that could potentially introduce latency when, for example, a participant attempts to place an object in a bin that has not been detected by the robot, or when a participant manipulates a target object outside of the field of view of the robot. Essentially, virtual objects remove the barrier between the view of the participant and the robot's understanding, as both human and robot can instead share the same knowledge of the environment. Eliminating the need for object recognition also increases the computational efficiency of the experiment, as more computational resources can be dedicated to simulating the interaction with and movement of virtual objects through 3D space, as well as the multitude of tasks assigned to the player, instead of being dedicated to task-irrelevant processes such as object recognition.

No Need for Motion Capture

Similarly, our use of virtual objects allows us to precisely track the exact positions of all task-relevant objects at each point in time throughout the experiment, as well as the exact moments in time when actions were taken on those objects (e.g., pick-and-place actions), as those actions can be automatically logged through the technology that enables them in the first place (i.e., the Hololens). This obviates the need for expensive Motion Capture systems and/or interaction garments that are otherwise often needed to precisely track participants' and robots' movements during human-robot interaction experiments (cp. [32]) (or costly manual annotation of such events from manual camera data analysis). The use of virtual objects, especially for the objects that participants interact with to place in virtual bins, also allows for their manipulation without the use of tabletop fiducials or a world-coordinate system (cp. [33]). Allowing the interactive virtual objects to be freely placed in space without the utilization of physical markers prevents unnecessary complications in the basic interaction design of the experiment, which could otherwise negatively impact the participant's ability to focus on the tasks they are given. Eliminating motion capture also eliminates the overhead of computationally-expensive algorithms for processing the resulting data. This is particularly important, because it is the standalone AR technology (i.e, the Hololens) that must render every virtual object within the experiment, rather than a desktop computer or other device with more computational power. As such, motion capture could potentially introduce processing delays that would have a negative impact on the ability for participants to seamlessly interact with virtual objects. Avoiding the use of motion capture simplifies the fundamental interaction systems within the experiment without detracting from the interactive experience of moving objects around.

Dynamic Environmental Changes Within Tasks

Our use of virtual objects allowed us to dynamically change the task environment during the course of a task, in ways that would not have been otherwise feasible. In the preliminary work discussed in this section, we aimed to study how different types of mental workload modulated the relative effectiveness of different communication modalities. One form of workload we were particularly interested in studying was visual perceptual workload, measured as the distinctiveness of target objects within a task with respect to distractor objects. By using virtual objects within our pick-and-place task, as soon as an object was picked-and-placed, it could be automatically replaced by a new virtual object, without experimenter intervention, according to a schedule that maintained a consistent level of visual similarity / dissimilarity within a task block.

Besides the virtual elements, the physical environment can also be dynamically manipulated using AR techniques beyond standalone AR headset. Lindlbauer et al. [34] designed a new form of mixed reality technique, Remixed Reality, that uses multiple RBG-D cameras to reconstruct live representation of an environment. Just as rendered geometry can be easily modified in real time in virtual reality, Remixed Reality allows easy changes in the physical environment, including spatial changes (e.g. erasing objects), changes in appearance (e.g. altering textures of objects), temporal changes (e.g., pausing time), and viewpoint changes (e.g. see a different viewpoint without moving to a new location). Future HRI experiments may leverage such system to manipulate a variety of important environmental features, such as the visual similarity / dissimilarity between physical and virtual objects. The knowledge of the physical environment enabled by this approach also allows virtual objects to be placed properly in the real world and facilitates even more natural interaction.

Within our own experiment, the ability to immediately repopulate objects within the experimental space provided many benefits not only in the pragmatics of running participants through the experimental paradigm (i.e. by allowing the experimenter to monitor interactions between the human participant and the robot, rather than making themselves an extraneous factor within the interaction), but also to the internal validity of the task bed itself. Maintaining steady manipulations of various cognitive resources requires a level of consistency within the stimulus presentation that would not be possible if a human experimenter were to manually set trials for individual participants. The use of the AR system also allows for better tracking of various measures that are relevant to determining the amount of workload a human participant is under during a given time period. Factors such as when a stimulus was presented as well as when a participant responded to that presentation can provide more nuanced information about the level of load an individual is under at that particular time than relying on participant performance metrics alone. The ability for experimenters to dynamically change the AR task environment therefore provides not only a pragmatic function, but also a level of rigorous measurement that would be unavailable, or difficult to implement, within in a purely naturalistic setting.

Dynamic Environmental Changes Between Tasks

Our experiment was executed as a within-subjects experiment in which participants were presented with a series of task contexts whose sets of constituent task objects varied with respect to visual similarity/dissimilarity. Our use of virtual objects allowed us to instantaneously provide new task contexts with carefully controlled placement of objects, without experimenter intervention, and without any opportunity for experimenter error in selection and placement of task-relevant objects. In fact, this allowed us to run a complex within-subjects experiment situated within a series of realistic pick-and-place task scenarios, without any need for experimenter involvement whatsoever during the experimental task.

Functionally, this allows the researcher to spend more time running tasks and collecting data than would have been possible in a situation in which an experimenter had to continually reset the scene for each individual task manipulation. Other experimental benefits are that the transitions between these different tasks allow for more tight control of what is presented to the user. The AR environment allows for more controlled periods of rest between task blocks. Though not directly used in our experimental paradigm, the ability to dynamically shift between different task configurations allows for algorithmic difficulty adjustments within an experimental paradigm that might be difficult to implement in a more traditional HRI experimetnal setup.

Reducing Extraneous Variables in Experimental Designs

In addition to adding the more robust environmental changes detailed above, the AR environment also reduced the need for the experimenter to change and manipulate physical objects throughout the experiment. Despite researchers best efforts to be consistent during wizard-of-oz studies, constant moving and manipulating of physical objects in our study by an actual human could have introduced any number of intentional extraneous variables into the experiments. For example, moving new blocks to and from the participant's table could be done unintentionally with slightly different timings, which would introduce variable amounts of time for the participant to perceive a new block, and their possible response time to search/sort could ultimately be effected. The effects of extraneous variables become magnified as the dependent measures in a study become more granular. For example, in the author's prior study [35] using non-invasive brain measurement (via functional near-infrared spectroscopy) to measure working memory load, the effects of extraneous variables were difficult to mitigate due to the sensitive nature of the brain measurement equipment. In that study, a virtual block (on the computer) was rotated while participants tallied the number of specific colors that they saw on the rotating block. There was an additional condition that mimicked the virtual block condition, where tangible blocks were actually placed in front of participants and spun in a circle manually by the researchers. Besides being difficult to spin in a circle consistently in all of the tangible block trials, there was also concern that motion artifacts were introduced into the brain data during the tangible block condition, because participants craned their neck to follow the spinning block on the table in a way that differed slightly from their movements while simply viewing the spinning block on a monitor. We include this anecdotal story to show how extraneous variables can be introduced that are caused by researcher error while manipulating physical objects in experiments, or via participant movement that are related to moving physical objects around in their environment. Clearly this 'physical movement' on the part of participants may not be as much of a concern if researchers are not including highly sensitive cognitive and physiological measurements in their study, but it is worth considering that even the NASA-TLX self-assessment of workload [36] contains a sub-scale item for 'physical load', and if there are any extraneous physical variables introduced in the study, that effect could find its way into the overall NASA-TLX score of workload.

2.2 Limitations

While augmented reality offers advantages in terms of enhancing the study of human-robot interaction, it also comes with several challenges:

Visual quality

Most headsets do not render virtual elements across the wearer's full scope of vision. The inability to cover peripheral vision obviates the user from achieving full immersion. In our HRI experiment where user was asked to interact with virtual objects, the illusion of a natural interaction disappeared when these objects got artificially cropped beyond the edge of the glasses' narrow field of view. Additionally, the visual fidelity of AR Head-Mounted Displays needs improvement to make the user more immersed in the experiment to the point that they forget they are wearing a headset. Enhancing the visual fidelity of the experience and increasing the field of view of the headset also bring with them another set of challenges relating to processing power and battery life. Our study utilized two Microsoft HoloLens 1, and they were switched every two hours to ensure that they both had enough battery to run for an entire day.

User Fatigue

The current generation of mixed reality headset may not be a good fit for tasks that require content to be within two meters and visualized at a high level of precision. Recent studies reports two optical problems that prevent participants from achieving task performance as well as the naked eyes [37]. A phenomenon called focal rivalry prevents human eyes from simultaneously focusing on both virtual and real objects. Another optical issue known as vergence-accommodation conflict stymies the natural ability of our eyes to focus at the correct distance. Our eyes naturally turn inwards to triangulate on an object as it approaches, but the lenses in headsets have fixed focal length. Attempting to manipulate virtual objects using software can't fool the eyes either. What is more, these two issues cause eye fatigue when the user is wearing the headset for some time.

In our experiment, we followed Microsoft's recommendation to design virtual contents to be 1-2 meters farther away from the user. We also gave participants breaks between each in-subject round so that eye fatigue would not affect the mental workload of the user, which was one of the factors we manipulated and measured. Though, future natural interaction experiments such as AR-assisted surgery and precise engineering repair may find the AR experience to be artificial when tasks require users to interact with content within arm's reach and to engage with content at any focal points.

3 Previous Work in Augmented Reality for Human-Robot Interaction

Finally, it is worth briefly summarizing how augmented reality is being used by other researchers in the context of human-robot interaction. Work on AR-for-HRI has slowly but steadily been progressing for at least twenty-five years [38–42], with the majority of work focusing either on increasing the flexibility of users' control over robots or increasing the expressivity of users' view into the internal models of those robots [43]. In the past few years, however, there has been a dramatic increase in work in the area [44, 45], with approaches being presented that use AR for robot design [46], calibration [47], and training [48], and for communicating robots' perspectives [49], understanding [50] intentions [51, 52] and trajectories [53–56]. Most relevant to this paper is work from Amor et al., who, while using projection-based rather than heads-up-display-based AR visualizations, explicitly use AR in order to *align perspectives* between humans and robots [57]. But to the best of our knowledge, there has been no previous work that has specifically reflected on the ability of AR technologies to increase the simplicity and control for experimental research in human-robot interaction. To demonstrate this effectiveness, we present a case study of the benefits gained by using AR in the context of a recent HRI experiment performed in our lab.

4 Conclusion

Augmented Reality and other spatial computing .paradigms stand to change the face of human-robot interaction, robotics in general, and in fact all of computing, in both academic research and its application in industry. In this paper we have discussed a number of advantages and disadvantages of also using Augmented Reality to facilitate the performance of such research itself. In future work it will be valuable to expand upon the insights provided in this paper to explore how other types of spatial computing paradigms may provide similar benefits to HRI researchers.

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