Enhancing Human-robot Collaboration by Exploring Intuitive Augmented Reality Design Representations

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ABSTRACT

As the use of Augmented Reality (AR) to enhance interactions between human agents and robotic systems in a work environment continues to grow, robots must communicate their intents in informative yet straightforward ways. This improves the human agent's feeling of trust and safety in the work environment while also reducing task completion time. To this end, we discuss a set of guidelines for the systematic design of AR interfaces for Human-Robot Interaction (HRI) systems. Furthermore, we develop design frameworks that would ride on these guidelines and serve as a base for researchers seeking to explore this direction further. We develop a series of designs for visually representing the robot's planned path and reactions, which we evaluate by conducting a user survey involving 14 participants. Subjects were given different design representations to review and rate based on their intuitiveness and informativeness. The collated results showed that our design representations significantly improved the participants' ease of understanding the robot's intents over the baselines for the robot's proposed navigation path, planned arm trajectory, and reactions.

CCS CONCEPTS

• **Human-centered computing → Mixed / augmented reality**; *User interface design.*

KEYWORDS

augmented reality, user interface design

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1 INTRODUCTION

There have been a burst of augmented reality (AR) applications to help improve HRI in different fields, mainly in the industrial setting. As we transition into an era of highly automated manufacturing, more emphasis will be given to improving how human agents interact and collaborate with robots in a work environment. These interactions have yielded remarkable results so far, but many HRI challenges remain. One such challenge is reducing the cognitive workload of a human agent when interacting with a robot via an AR interface, especially one unfamiliar with the system. Poor communication of robot intention and planned movements can cause hazards in the work environment that might jeopardize safety, reduce task efficiency, and lead to flawed perceptions of robot usability [14]. However, active research is currently being carried out to address these issues. AR has had a significant impact on enhancing human-robot collaboration in the workspace in different ways. It has been used for robot programming and motion planning to instruct robots on task execution [12], [6]. This could be by issuing either low-level [12] or high-level goals [6] where the robot figures out the best way to execute the request. AR has also been used to communicate the robot's intentions, such as warning alerts, proposed path, arm motion, and trajectory to the agent.

In our work, we outline and discuss a set of design guidelines that should be followed when designing AR interfaces for HRI systems. These guidelines not only ensure that interfaces are designed as intuitively as possible for a novel user, but also provides systematic best practices for an HRI researcher when developing HRI interfaces. In order to illustrate the usage of the guidelines, we have developed sets of interface designs for various types of robot feedback during the course of a robot's interactions with a human agent in a work environment. These interfaces include the proposed robot navigation path, proposed robotic arm end-effector trajectory, and alert and warning displays. Safety and trust of both the robot and the human agent(s) are two important factors to be considered when designing HRI systems, and in our work, we have explored the AR design space in order to develop interfaces that would enhance these factors whilst also ensuring a reduced task completion time. To evaluate our proposed design frameworks, we created a survey where the participants gave different ratings for the various interface designs.

2 RELATED WORK

State-of-the-art manufacturing systems [5] has created the need to reduce the complexity that arises from a hybrid work environment [3]. As noted in [7], there should be tools that can conceal these complexities from human agents and help them communicate and interact with the rest of the system. Furthermore, [7] noted that these tools must offer easy-to-use interfaces with an intuitive mechanism that should not distract the workers from their tasks. Here, they designed an application that doesn't require a human agent to have specialized knowledge or training. However, the interface was cluttered with many buttons, which could make the human

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agent have difficulties figuring out the right button to press. In our work, we tried to avoid this clutter by limiting the number of view items that we overlay on the agent's screen.

Georgios et al. [12] proposed a system that allows for bidirectional communication between a robot and multiple users in a work environment in real-time. This work may not have represented the design of their AR application in a way that would be intuitive for the agents. For instance, in the paper, the end-effector's planned trajectory was represented using a 3D sphere and the arm movement radius as a red transparent sphere. However, using red for this purpose could be misinterpreted to mean danger or a problem. Our system explores different design representations for capturing the robot's planned trajectory, making it easier for a human agent unfamiliar with the system to grasp it quickly.

Lotsaris et al. [9] used an AR application to provide functionalities such as robot motion and workspace visualization, visual and audio alerts, and production data. Here, operators can visualize all the components involved in the assembly sequence intuitively using 3D models. Their proposed approach, despite its innovative audio alerts, is less informative than it could be. The text on the visual alert is blurry and the 3D model lacks sufficient fidelity and might be challenging for a novel operator to understand and navigate. In contrast, in our proposed framework, we have ensured that the design of the interfaces is very simple and easy even for an untrained user. We also ensured that our 3D models have high fidelity.

Robot trajectory planning is one of the most important aspects of a human-robot interaction system and research have been carried out to improve and achieve better results. Fang et al. [4] designed a high-fidelity AR-based virtual manipulator which facilitates robot programming and trajectory planning. Despite the high fidelity of the interface and the accuracy achieved by the simulated motion planner, the presented system would pose a challenge to a less technical user given the level of technical sophistication and low intuition provided by the system.

3 AR DESIGN BEST PRACTICES AND GUIDELINES

When designing AR interfaces for HRI purposes, it is important to follow specific laid-out guidelines. These rules not only ensure that interfaces are designed appropriately for new and experienced users, but they also provide a systematic approach for the researcher towards designing interfaces for HRI systems. Radkowski et al. [11] proposed that the level of difficulty of carrying out a task during a manual assembly process should determine the complexity of the user interface (UI). The factors to be considered include the number of moving directions of a part, the number of active surfaces the operator needs to keep aligned during a joining procedure, the number of parts and operations in the assembly task, the hierarchy of parts and operations in the assembly task, the visibility of the part to assemble, and lastly, the posture of the operator. However, the authors noted that these parameters can be difficult to quantify, but with formal user studies using interface prototyping, the assessment can be facilitated. Furthermore, Danielsson [1] discussed a concept called "design science" which aims at developing ways to achieve human goals through the creation of artifacts that are evaluated to ensure they meet the design requirements. Wilkinson et al. [15] also proposed some guidelines which should guide the design of interfaces for HRI systems. The authors discussed the implementation of these guidelines using two UIs they developed. We have also applied these guidelines to our work. Below is a description of the guidelines and how we adhered to them.

3.0.1 Understandable. [15] stated that since HRI systems should be simple even for an untrained user, the UIs must offer enough feedback and intuition to allow for ease of understanding and use. Our proposed the framework used basic visual features which most people are familiar with, such as arrows and cones, thereby offering good intuition to the users and reducing task completion time.

3.0.2 Reliable. Since the real world cannot be completely predictable, there are chances that the user might make errors. A well-designed HRI system should have a robust error-handling capability [15]. We adhered to this guideline by designing some sets of visual alerts which give a user a proper visualization of the status of the robot, enabling the user to avoid cases that could cause harm to them or the robot.

3.0.3 Accessible. The HRI system should be able to be used by various people with different physical and cognitive abilities. In our system, we ensured that visual features such as labels, arrows, and cones are not only accessible but also very legible and informative to all users. Furthermore, [2] discusses some Human-Computer Interaction (HCI) principles could serve as guidelines for designing AR systems. We have extended and incorporated this set of guidelines in our work. Below we discuss the guidelines most relevant to AR applications for HRI purposes.

3.0.4 Low Cognitive Overhead. An AR interface should be designed in a way that would enable the user to focus on the actual task and not get distracted by unimportant information, helping reduce the agent's cognitive overhead. According to [15], registration errors in AR systems could reduce the performance of users when the virtual elements from the AR interface are not well aligned with the physical objects. The result of this could lead to a reduction in task performance since associating the virtual elements with the physical environment requires cognitive effort from the user [2].

3.0.5 Learnable and Consistent. A good user interface should enable users quickly to learn how to navigate an AR application. Maintaining a consistent interface, in both appearance and functionality, is essential for this purpose. In our work, we have ensured that we maintained a consistent look and feel of the user interface. We used consistent color schemes, object shapes, and dimensions to ensure uniformity and coherence.

3.0.6 Responsive. It is essential that AR applications are designed with responsiveness in mind. It is almost impossible to rule out the occurrence of lags in an application. Therefore, an AR application should be designed to provide feedback to the user whenever such occurs. This helps keep the user informed and less anxious.

The proposed design frameworks adhered to the above guidelines which ensures a systematic approach to designing AR interfaces for HRI systems in order to achieve informative and intuitive interfaces.

Figure 1: Different robot feedback warning alert designs.

4 TECHNICAL DESCRIPTION

Our work uses a 3D/AR Unity application to explain and recommend the different ways AR interfaces should be designed to enhance Human-Robot collaboration in a work environment. We undertook an iterative process to explore the design space of AR-HRI systems by providing intuitive and concise feedback on robot motion intent and obstructions identified by the robot. We evaluated several past AR-HRI systems across different application scenarios and came up with a base for a high-level framework on how to design and represent robot feedback in an AR-HRI system for enhanced human-robot interactions.

We implemented our proposed HRI system using the open-source simulated Niryo One robotic manipulator, a collaborative 6-axis robot in the Unity 3D environment. It was provided by [10] in the form of a Unified Robot Description File (URDF) [13], which is similar to what was used in [16].

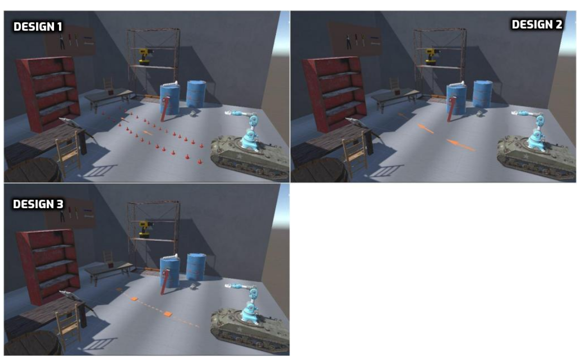

Figure 2: Different proposed robot navigation path designs

5 EXPERIMENTAL EVALUATION

In this section, we will discuss the problems identified in the design of interfaces for AR-HRI systems and evaluate our proposed solutions. Our proposed solution tries to classify the interfaces into three broad categories: visual alerts, robot navigation paths and workspace visualization, and robotic arm end-effector manipulation and object pickup. These designs were evaluated by recruiting 14 participants who were presented with the different design representations of our system in an online survey. The designs were presented in the order: path-arm-alert and they were asked to express their thoughts about the designs, how quickly they were able to figure out what the designs were about, and how intuitive the designs were. These responses in addition to the Likert scale ratings were collated from the participants.

5.1 Visual Alerts

Visual alerts could be general messages designated by the process planner [8] or more specific alerts like the path of the robot. Due to the impact of these alerts in determining both user and robot safety in the work environment, it is crucial to ensure that the the information they convey is intuitive and easily understood by human operators without requiring much cognitive effort. The alert interfaces in previous AR-HRI systems are often either illegible due to poor choice of color and font or are cluttered with so many views items that the messages are challenging for the human operator to understand. This can be seen in [8] and [7].

To address this challenge, we proposed four different visual alert design representations (see Figure 1) which were evaluated by the survey participants.

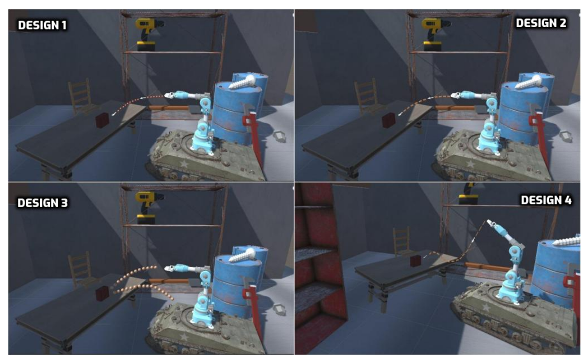

Figure 3: Different planned robot arm trajectory designs

5.2 Robot Navigation Path and Workspace Visualisation

Robot navigation and path planning are essential aspects of an HRI system. A poorly designed visual representation of the robot's planned the path is likely to lead to confusion in the work environment among the human operators, which not only has the potential to harm the operators but also increases the production time. In [12], the planned robotic path was represented using a set of 3D green spheres and has no similarity with real-world path indicators, introducing the potential of being misunderstood by an operator unfamiliar with the system and environment.

We have addressed this challenge by applying familiar real-world design representations and concepts such as traffic cones and road barriers to developing three different design representations of robot navigation paths (see Figure 2) that have been evaluated and rated by the survey participants.

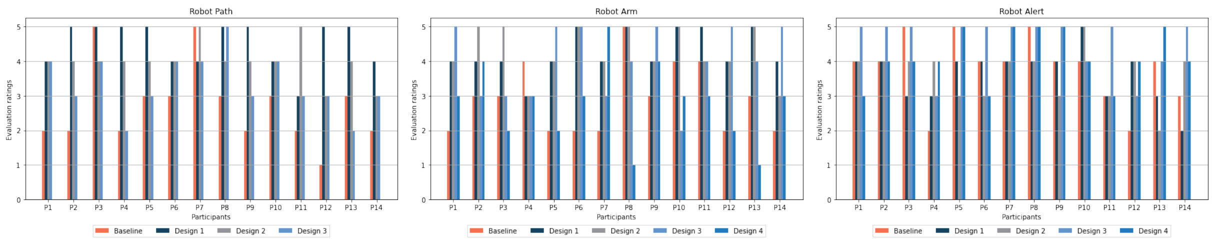

Figure 4: User ratings for the robot proposed navigation path, planned arm trajectory, and alert designs

5.3 Robotic Arm End-Effector Manipulation and Object Pickup

Augmented reality has often been used to plan the path and orientation of the end-effector of a robot. However, adequate measures should be taken to ensure that these paths are represented in the design space intuitively, avoiding complexity whenever possible. Just like their proposed robot navigation path, [12] represented the proposed path of their end-effector using a set of green 3D spheres that made an oval shape. This design concept could potentially confuse the operators, especially those unfamiliar with the system because they failed to use familiar and conventional view elements to represent paths and trajectories in the physical world. To address this, we have evaluated several design approaches to represent the planned paths and trajectories of end-effectors (see Figure 3).

6 RESULTS & DISCUSSIONS

This section summarises our findings based on the survey involving 14 participants. The designs were reviewed based on their intuitiveness, informativeness, and proximity to natural and familiar representations. The participants were asked to rate the proposed methods and the baseline methods ([12], [9], and [4]) on a 5-point Likert scale (see Figure 4).

6.1 Proposed Navigation Path

The first subfigure shows the survey results for the different robot navigation path designs. Most of the participants had difficulty understanding the robot's intent when they were presented with the baseline's representations. However, our approach significantly improved the participants' understanding of the robot's intent. The Design 1 representation was the most informative and imposed the least cognitive overload to the participants.

6.2 Planned Arm Trajectory

Results for the proposed robotic arm trajectory designs are shown in the second subfigure. In this category, the baseline approaches were also rated as less informative by most of the participants compared to our proposed approaches. However, most participants rated their understanding of the proposed designs as either neutral or informative. Thus, the proposed approaches did not significantly improve the users' understanding of the robot's intent.

6.3 Alert

The third subfigure shows the survey results for the various robot reactions designs, such as warning alerts. The participants rated our baseline approaches as informative. In contrast, our proposed designs provided a more explicit representation of the robot's intent to the participants and most participants rated them as either informative or very informative.

We found a significant effect of design on perceived communication clarity, which translates to the user's perception of the robot as a good work partner. Aside from the ratings of the presented designs, some participants left important feedback regarding how they felt during their evaluations of the different designs.

- Participant X [Arm Trajectory]: "At first, I thought the robot was shooting cannon balls at the object."
- Participant Y [Arm Trajectory]: "Is this trying to represent projectile motion or something of that sort?"
- Participant Z [Navigation Path]: "I initially didn't understand what the dotted colored lines on the floor meant. It took me a while to figure it out."

Interestingly, some participants found some of the design representations from the baseline methods to be more informative than some of our design representations in some categories. However, the same participants rated at least one of our proposed designs higher than all the baseline approaches, even in those cases.

7 CONCLUSIONS & RECOMMENDATIONS

This research explored the design space of human interactions with a robot through AR to convey the robot's intentions. We conducted a survey involving 14 participants, where each participant was presented with different design representations which they rated against the baseline approaches from previous work. We found that they were able to easily and more quickly understand the intents of the robot at the different stages of the human-robot collaboration cycle. From the results, we note that our proposed representations significantly improved their understanding of the robot's intents over the baseline approaches.

The aim of this work was to introduce a systematic approach to designing AR interfaces for HRI systems to ensure that they adhere to the best practice of providing a very limited cognitive workload to the users. From the statistics of our collated results, we could see the impact our proposed design representations made on the participants in terms of the ease of understanding the robot's intents, hence we believe this aim was achieved. Therefore, we recommend our approach as a base for researchers exploring ways to improve the usability of their HRI systems, especially when designing their robot's visual feedback systems for conveying robot intentions and messages to human agents.

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