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Augmented Reality Safety Zone Configurations in Human-Robot Collaboration: A User Study

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Abstract

Close interaction with robots in Human-Robot Collaboration (HRC) can increase worker productivity in production, but cages around the robot often limit this. Our research aims to visualise virtual safety zones around a real robot arm with Augmented Reality (AR), thereby replacing the cages. We tested our system with a collaborative pick-and-place application which mimics a real manufacturing scenario in an industrial robot cell. The shape, size and visualisation of the AR safety zones were tested with 19 participants. The overwhelming preference was for a visualisation that used cylindrical AR safety zones together with a virtual cage bars effect.

1 Introduction

The use of physical cages in human-robot interaction is normal according to safety standards, but these cages can negatively impact on human-robot interaction [8, 5, 4]. Research suggests that removing cages around robots will enhance human-robot interaction possibilities, thus providing flexibility and efficiency [5, 6], but this brings safety risks. To mitigate such risks, Augmented Reality (AR) can be used [9, 11]. Here, a range of approaches have been used to display safety zones, including 2D areas [7], safety curtains [5], user-configurable barriers (including around the user) [6] and geometric objects [2, 1].

In our previous study [1], we proposed safety zones based on transparent geometric shapes and described how to calculate the size of these based on ISO standards and network latencies. In this new study, we investigate different ways to customise the safety zones and how this affects user feelings such as safety and trust. We tested virtual safety zones of different shapes, sizes and renderings with 19 participants in a pick-and-place application that mimics a spot welding process used in industry. We believe we are the first to employ a virtual cage bars effect in the rendering of the safety zones. Our study uses a Microsoft's HoloLens 2 and a Universal Robots 10 (UR10) robot arm.

The rest of this paper is as follows. Section 2 describes the pick-and-place application and discusses AR visualisation. Section 3 presents the user study results. Finally, section 4 gives conclusions.

2 Study Design

The aim of the study was to compare alternative ways to display the shape, size, and appearance of a virtual cage around a robot arm in a collaborative pick-and-place task and consider how this influences perceptions of safety.

Figure 1: The robot arm picks up a wooden block from area A and moves it to area B, the middle of the table. The user then picks up the block from B and places it in the plastic container (area C).

Whilst a physical cage is typically a fixed-size, static cuboid, a virtual cage can be dynamic in size, meaning the user can get closer to the robot arm. We chose two shapes: (i) a traditional cuboid cage shape with the size changing depending on robot arm configuration (an axis-aligned bounding box); (ii) a collection of cylinders which best matched the the shape of the main pieces of the robot arm. Figure 1 shows the experimental setup with virtual transparent cylinders (as would be viewed through the HoloLens 2 headset) surrounding the robot arm. These warn the user to stay out of this area. The robot arm moves wooden blocks in turn from A to B and the user moves each block in turn to area C. Each experiment participant completed this pick-and-place task four times, once for each different configuration of the safety zone. The order of configurations was varied for each participant to counter any order effects.

The four different safety area configurations used were:

- Small cuboid: A dynamically-sized, cuboid (axis-aligned bounding box) virtual cage that completely covers the robot arm and is based on the position of the robot arm and the ISO 15066 standard [3]. The ISO standard give guidelines for the distance between the parts of the robot arm and the operator - we use for calculating the size of the safety zone;
- Large cuboid: A dynamically-sized, cuboid (axis-aligned bounding box) virtual cage that completely covers the robot arm and is based on the position of the robot arm and the ISO 15066 standard with an extra safety layer for hardware and network latencies;
- Small cylinders: Cylinders around the three main parts of the robot arm. These are sized according to the ISO 15066 standard and do not change in size dynamically;

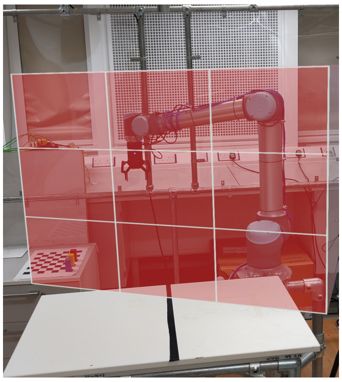

Figure 2: Large cube with thin opaque bars

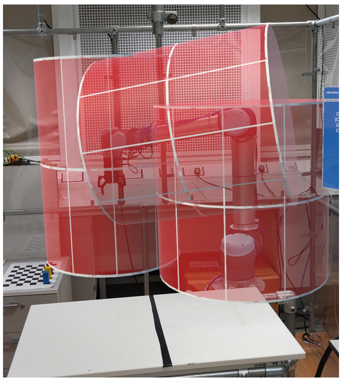

Figure 3: Large cylinders with thin opaque bars

- Large cylinders: Cylinders around the three main parts of the robot arm. These are sized according to the ISO 15066 standard and do not change in size dynamically. The radius of the cylinders is larger than for the small cylinders since it also includes compensation for hardware and network latencies.

The experiment was split into two phases, with different visualisations in each phase, as given in table 1. The default is a red, transparent cuboid or cylinder (figure 1). In some configurations, virtual bars were also added, as shown in figures 2, 3, 4 and 5. Our hypothesis was that these would help delineate the safety zone. 14 participants conducted the first phase, with 5 participants in the second phase. The reason for two phases was because of comments by most of the participants in the early stages of the experiment. It was clear that the visualisation of cage bars was important, so we decided to change the experiment for the last 5 participants and add virtual cage bars to all configurations to see how this impacted on the results, thus creating a second phase of the experiment. In order to gain the best AR experience, each user completed the eye calibration process with HoloLens 2 before starting the experiment.

Each participant completed a questionnaire at the end of their participation. A five-point Likert scale (strongly disagree, disagree, neither agree nor disagree, agree, strongly agree) was used for the questionnaire, and users were asked to explain their preferences in short paragraphs for each specific answer. The questions for phases 1 and 2 are given in table 2. For phase 2, the preamble to the questions and the questions on visualisation (Q7a and Q7b) were altered to mention the virtual cage bars for the four configurations. (We decided to label the semi-transparent bars in phase 2 as translucent/half-transparent so as to make the differ-

Figure 4: Small cube with thin transparent bars

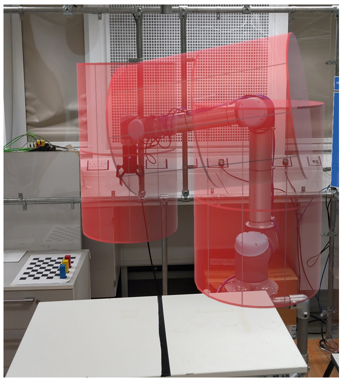

Figure 5: Small cylinders with thin transparent bars

	Phase 1 (14 participants)	**Phase 2** (5 participants)
Small cuboid	no bars	transparent bars
Large cuboid	opaque bars	opaque bars
Small cylinders	no bars	transparent bars
Large cylinders	opaque bars	opaque bars

Table 1: Visualisation in each phase. In each configuration, a red, transparent shape was used. The difference in configurations is whether virtual bars were also added to the visualisation.

Configurations
Q1 This configuration made it easier for me to do the task than the other configurations.
Q2 This configuration made me trust the robot arm when I was doing the task.
Q3 This configuration made me feel safe when I was doing the task.
Q4 I would choose this configuration if I had to do a similar task again.
Q5 Please put the configurations in your order of preference. Your preferred best configuration should be rated as 1 and the others 2, 3, and 4. Tick the relevant boxes accordingly.
Use of Hololens 2
Q6a I found the HoloLens 2 easy to use.
Q6b I found the HoloLens 2 to be comfortable to use.
Visualisation
Q7a (Phase 1:) The red transparency effect without the virtual bars worked well for displaying the safety zones.
(Phase 2:) The red transparent effect combined with "the translucent (half transparent) white cage bars" worked well for displaying the safety zones.
Q7b (Phase 1:) The red transparency effect with the virtual bars worked well for displaying the safety zones.
(Phase 2:) The red transparent effect combined with "the opaque white cage bars" worked well for displaying the safety zones
Q7c Red is a good colour to use for the safety zone display.
Q7d The cuboid safety zones dynamically changed in size during the experiments. I did not find this distracting.
Q7e Overall, I thought the safety zones were well displayed.
The System
Q8a I was confident whilst doing the task using the system.
Q8b Interaction with the robot arm was easy using the system.
Q8c I think that I would need the help of a technical person to use the system in the future.
Q8d I would imagine that most people would learn to use this system quickly.
Q8e When I made a mistake or the robot made a mistake, it was easy and quick to recover and continue with the task.

Table 2: The questions used for phases 1 and 2. Questions 7a and 7b are different for phase 2.

		Phase 1					**Phase 2**				
Likert scale:		Strongly disagree	Disagree	Neither disagree nor agree	Agree	Strongly agree	Strongly disagree	Disagree	Neither disagree nor agree	Agree	Strongly agree
Configurations Small cuboid	Q1	-	-	-	-	-	-	-	-	-	-
Large cuboid		-	-	-	3	-	-	-	-	-	-
Small cylinders		-	-	-	-	-	-	-	-	2	-
Large cylinders		-	-	-	3	8	-	-	-	1	2
Small cuboid	Q2	-	-	-	-	-	-	-	-	-	-
Large cuboid		-	-	-	2	3	-	-	-	-	-
Small cylinders		-	-	-	1	1	-	-	-	2	-
Large cylinders		-	-	-	1	6	-	-	-	-	3
Small cuboid	Q3	-	-	-	-	-	-	-	-	-	-
Large cuboid		-	-	-	2	3	-	-	-	-	1
Small cylinders		-	-	-	-	1	-	-	-	1	1
Large cylinders		-	-	-	2	6	-	-	-	-	2
Small cuboid	Q4	-	-	-	-	-	-	-	-	1	-
Large cuboid		-	-	-	3	1	-	-	-	-	-
Small cylinders		-	-	-	1	-	-	-	-	-	2
Large cylinders		-	-	-	-	9	-	-	-	-	2
HoloLens 2	Q6a	-	2	-	10	2	-	1	-	2	2
	Q6b	-	1	1	7	5	-	1	-	1	3
Visualisation	Q7a	1	7	2	3	1	-	2	-	3	-
	Q7b	-	-	-	1	13	-	-	-	1	4
	Q7c	-	-	2	3	9	-	-	-	2	3
	Q7d	1	-	-	4	9	-	1	1	1	2
	Q7e	-	-	-	7	7	-	-	-	2	3
The System	Q8a	-	-	-	3	11	-	-	-	3	2
	Q8b	-	-	-	2	12	-	-	-	1	4
	Q8c	6	6	2	-	-	2	1	1	1	-
	Q8d	-	-	-	6	8	-	-	1	4	-
	Q8e	-	-	-	5	9	-	-	1	2	2

Table 3: Number of replies for each question (where - means 0 to reduce visual clutter).

ence stand out, although technically they are not translucent as they are not scattering light.) For each participant, the AR experience took approximately 30 minutes and the questionnaire was timetabled for 30 minutes. None of the experiment participants had any previous experience with AR. 16 participants were men and three women.

In order to mitigate risk during the experiment, 3 measures were implemented. First, the system detects when a user's hand penetrates the virtual safety zone surrounding the robot arm and the robot arm immediately stops. The user can start the movement again after moving their hand out of the visualisation zone. Second, the researcher monitors the experiment and can press a physical stop button for the robot arm. Third, the robot arm is operated at a low speed so that potential collision forces remain below pain thresholds for the hand and arm (as given in [10]). All participants were paid for their contribution and ethics permission was obtained by the university ethics procedure.

3 Results and Discussion

As noted in section 2, the experiment was conducted in two phases. 14 participants took part in phase 1 and 5

	Phase 1				Phase 2			
Rating:	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**
Small cuboid	1	1	1	11	1	-	2	2
Large cuboid	3	6	5	-	-	1	2	2
Small cylinders	-	5	6	3	1	3	-	1
Large cylinders	10	2	2	-	3	1	1	-

Table 4: Numbers of users who ranked each configuration (question 5) for phases 1 and 2, where the rating is 1=best and 4=worst. Note that - means 0 to reduce visual clutter in the data cells.

participants took part in phase 2, with the configurations for each phase given in table 1. Table 3 gives the results for the phase 1 and 2 questions (excluding question 5 since this used a different scale).

3.1 Phase 1

For phase 1, the results in table 3 makes it clear that large cylinders with opaque bars were preferred by participants. Users said it was easier to observe the boundaries of the cylinders when they were moving. Some users commented on the large cuboid giving the impression of a wall or a large volume, and they feared it would hit them when it moved. Commenting on question 4, users said they would use the large cylinder configuration as it was easier to understand the robot arm's motion and they felt safer.

Table 4 gives the results for question 5. The larger cylinder was the preferred option. In this case, the reasons centred on the use of the virtual cage bars. The users said this increased perception of depth. Some users said they preferred smaller safety volumes, but the use of virtual bars meant they chose the large cylinders because it made the volume clearer. Question 6 focused on use of the HoloLens 2 headset with most users finding it comfortable to use.

Question 7 focused on the visualisation of the safety zones. For phase 1, questions 7a and 7b showed that the visualisation of virtual cage bars was preferred. Question 7c suggests that red is an acceptable colour to show the safety zones. Question 7d considered the cuboids which dynamically change size whilst the robot arm is moving so as to always maintain ISO standard distances around the robot arm. Users did not find this distracting. Overall, as shown by question 7e, users felt that the safety zones were displayed well.

Question 8 focused on the overall system. Questions 8a and 8b suggest participants were comfortable using the system to complete the task. Interestingly, despite not having AR experience, the participants did not need extra help to use the system. The two participants who answered 'neither agree or disagree' were the same two participants who found the HoloLens 2 less comfortable to wear (question 7b). Question 8d asked them to speculate how quick it would be for others to learn to use the system. The answers were positive. Finally, question 8e asked about system recovery in the event of an error. The system uses floating menus for configuration purposes (although the configuration menus were not available to users in this experiment) and a pop up menu immediately appears if the safety zone is violated. The user can then click a button (using the Hololens 2's ability to track the user's hands) on the floating pop-up box in the 3D space to continue the experiment. Most users found this easy to use.

3.2 Phase 2

The results of phase 2 are limited, since there were only 5 participants. In phase 2, all the experiment configurations had virtual cage bars, although they were transparent bars for the smaller volumes. Based on the data in tables 3 and 4, cylinders appear to be preferred in general, which supports the results of phase 1, and opaque cage bars on a large cylinder were preferred over the transparent virtual cage bars, even if the safety zone was larger.

3.3 Discussion

Overall, based on the results of phase 1 and 2, a combination of cylinders and opaque virtual cage bars was the preferred configuration. The reasons why the virtual cage bars were preferred was that they made the safety zone more precise, increasing depth perception and making the edges of a safety zone clearer. The reason why cylinders were preferred was probably because they matched the shape of the robot arm pieces and thus contained less dead space than the cuboids, increasing the perception of closer collaboration.

Another aspect we were interested in was the issue of trust in human-robot collaboration. Users commented that the opaque virtual cage bars increased their trust in the robot arm and helped them also overcome any initial fear. [2, 1] had only used transparent volumes, in line with other work that has used AR. It is clear from our results that the virtual cage bars are an important addition for increasing trust. Two users commented on the level of transparency of the virtual shape, suggesting that the shape could be made more transparent.

One disadvantage of using the HoloLens 2 for AR is its narrow field of view (43° horizontal, 29° vertical, 52° diagonal). A few users commented on this. Whilst the field of view is a significant improvement over the HoloLens 1, it still does not display the entire working area of the robot cell in our experiment. Instead the user has to move their head to view all of this.

4 Conclusions

We have used a collaborative pick-and-place application to test user's opinions on the size, shape and visualisation of safety zones when interacting with a robot arm. The clear result is that users preferred the use of a combination of cylinders and virtual cage bars, as the virtual cage bars better delineate the safety volumes. They also commented on increased trust levels when collaborating with the robot arm with this configuration. In future work, we intend to test our system in a real industrial setting.

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