A Demonstration of the Taxonomy of Functional Augmented Reality for Human-Robot Interaction

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***Abstract*—With the rising use of Augmented Reality (AR) technologies in Human-Robot Interaction (HRI), it is crucial that HRI research examines the role of AR in HRI to better define AR-HRI systems and identify potential areas for future research. A taxonomy for AR in HRI has recently been proposed for the field. However, it was limited to the definition of the framework, and exemplifying its use was missing. In this paper, we perform a demonstration of how the aforementioned taxonomy of AR in HRI can be used to analyse an existing AR-HRI system and come up with questions for alternative ways AR-HRI could be designed and further extended.**

***Index Terms*—Human-robot interaction, augmented reality, taxonomy, demonstration**

I. Introduction

A major component of Human-Robot Interaction (HRI) is communication between human and robot. Augmented Reality (AR) technologies facilitate this as they enable the superimposition of digital content on the real-world environment, allowing better comprehension and additional ways of interaction between human and robot [1]. As AR is becoming common in HRI [2], it is beneficial for HRI researchers to utilise a design framework to instigate questions on existing works to better understand and extend boundaries. We proposed a taxonomy on the functional role of AR in HRI in [3]. The taxonomy provides three key dimensions of functional AR-HRI: 1) high-level functional roles of AR in HRI, 2) perception augmentation classification, and 3) types of AR artifacts.

1) The high-level functional roles of AR-HRI are comprised of:

- Augmented Comprehension of the Present Reality: where AR provides further information to the human about the present physical reality,
- Artificial Timescale: where AR provides information to the human about a situation in the past, future or in an imaginative scenario, and
- Augmented Control: where AR provides greater control of the robot to the user.

2) The perception augmentation classification distinguishes whose perception - the human's or the robot's - is being augmented with AR, and which part of this perception is being augmented - the perception regarding the human, robot or environment. Altogether, the categories are:

TABLE I: Design A's functionalities and 1) their perception augmentation types, 2) their AR functional roles, and 3) their augmentation artifact types

Functionality	Augmented Perception: Human			Augmented Perception: Robot			Function			Artifact			
	Robot	Environment	Self	Human	Environment	Self	Artificial Timescale	Augmented Comprehension	Augmented Control	Augmented Embodiment	Augmented Interactive Objects	Augmented Scene	Augmented UI
AOG display	●	●	○	○	○	○	○	●	○	○	○	○	●
AOG patching	●	●	●	○	●	●	○	●	●	○	○	○	●
Sensory info display	●	●	○	○	○	○	○	●	○	○	●	●	○
New action input	●	●	●	●	●	●	○	●	●	●	○	●	●
Robot gesture control	●	●	○	●	●	●	○	○	●	○	●	●	○
Range warning	●	○	●	○	○	○	○	●	○	○	○	●	●

●=Yes; ○=No.

- Human Perception Augmentation
  - Augmented Human Perception of Robot
  - Augmented Human Perception of Environment
  - Augmented Human Perception of Self
- Robot Perception Augmentation
  - Augmented Robot Perception of Human
  - Augmented Robot Perception of Environment
  - Augmented Robot Perception of Self

3) Lastly, the types of AR artifacts classify what the virtual AR artifact is being used for:

- Augmented User Interface: for acting as the user interface,
- Augmented Embodiment: to be an embodiment or part of an agent,
- Augmented Interactive Object: to act as an interactive object, or
- Augmented Scene: to simply help to present the AR scene.

To demonstrate the use of the defined taxonomy, we use work presented by Liu et al.'s [4]. In their work, the AR HoloLens application mediates the interaction between the user and the robot for the accomplishment of a medicine bottle-opening task. The user is able to view the And-Or Graph (AOG) of the robot's learned knowledge representation, teach it new actions, and modify its knowledge structure (Figure 1). This addresses many issues raised within interactive agent learning research concerning human-agent bidirectional communication [5]. In particular, the system allows for the user to be aware of the robot learner's mental model and therefore the user is able to appropriately teach the robot learner. This is an important part of effective human-human teaching and it also extends to HRI [6].

In this paper, we examine Liu et al.'s design [4] by utilising the taxonomy of functional AR-HRI as proposed in [3] as a design framework (Table I). We demonstrate how it can be used: 1) to assess the AR-HRI functional design and 2) to design an AR-HRI work. We present potential ideas, deriving them from existing literature in hopes this can help future researchers design their AR-HRI systems. The goal of our design extension is not to imply that it must be implemented in the next iteration of the system, but rather to suggest the potential in the advancement of AR-HRI when using a design framework. We refer to Liu et al.'s original work [4] as Design A, and our extension as Design B.

II. Functional Role of Augmented Reality

In this section, we utilise the functional role dimension of the taxonomy to analyse Design A and propose potential changes to develop Design B. The categories in this dimension as proposed in [3] are: a) Augmented Comprehension of the Present Reality, b) Artificial Timescale, and c) Augmented Control.

1) Augmented Comprehension of the Present Reality: The AR interface in Design A falls under the functional AR role of Augmented Comprehension of the Present Reality; the system allows for the user to acquire additional information about the current physical reality. It provides to the user an AOG representation of the robot's knowledge, allowing the user to understand how the robot behaves and the reasoning behind it.

Although the system's present functionalities can be described under this category, we present additional possible functionalities from this category for the system. AR is being used for the user to better understand the robot. However, in a typical HRI scenario, the human and the robot are not the only entities present; the environment is also involved. We can therefore question if AR could provide any further information about the scenario to the user. In previous research [7] [8], AR has been employed to inform the user of objects in concealment. Applying this concept, Design B would allow for the user to know about the content inside the bottle. It shall be able to identify the name of the medicine from the bottle and present this information without the user having to grab the bottle to examine. In addition, readily informing the user how much of the bottle content remains (as a percentage, for instance) without having to open the bottle would provide convenience to the user. The ability to know the content of the bottle and the amount of it would particularly be useful for users with poor eyesight, especially in elderly patients who may rely on medicines more heavily.

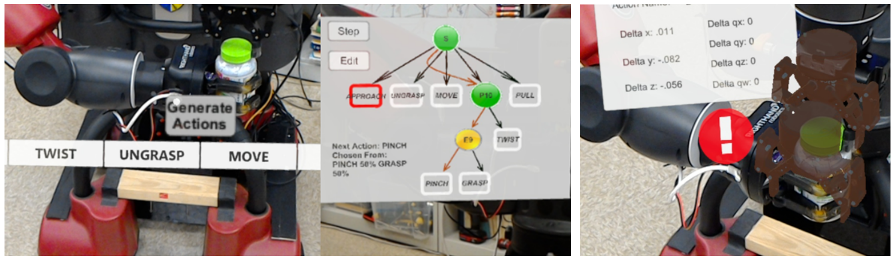
2) Artificial Timescale: Although Design A does not fall into the functional AR role of Artificial Timescale, we propose some of this category's functionalities for Design B. The ability to plan in robotics is crucial [9]. The user may be teaching the robot new material without realising if the robot has learned in the intended way. The ability to preview the actions of the robot can help the user to identify 1) if the user needs to teach the robot at all, 2) if the robot has learned correctly from the user, and 3) what corrections the user should be making to the robot. Like in previous AR-HRI research [10], [11], in this preview, the virtual robot model shall be superimposed on the physical robot, performing the intended trajectories in AR. By presenting a preview to the user, this avoids accidental damages to the bottle or to the robot which could occur from incorrect performance. It could also increase human safety.

Utilising Artificial Timescale to look into the past, history logs of the procedures performed by the robot and whether they were completed successfully could help the user to easily identify areas which may need to be debugged, and the version the user can quickly switch to in the future.

3) Augmented Control: Design A already provides this functional role, Augmented Control, to the user. It gives the user the ability to modify the robot's knowledge of action definitions and knowledge structure to complete the task. The system also allows the user to control the robot's gestures. In order to extend the existing functionalities of Design A, Design B would give the user the ability to use the AR interface to instruct the robot to open the bottle, when to automatically open it, and which bottle to open. In previous research, AR has been used for robot control via tongue movements [12] and eye gaze [13], [14], including for individuals with paralysis. AR could be a way to extend technologies to a wider range of users.

III. Perception Augmentation

From our analysis of the functional role of AR, we can summarise the additions to Design A to create our Design B according to the three functional roles. Firstly, Design B now gives the user the ability to plan/preview the robot's actions as well as provides logs (Artificial Timescale). Secondly, more information about the scenario is given to the user (Augmented Comprehension of the Present Reality). Lastly, more control is provided to the user (Augmented Control). In this section, we further formulate additional design ideas by examining the next dimension of the AR-HRI taxonomy: the augmentation of perception. Here we examine whom the perception which is being augmented belongs to (human or robot), and which part of the perception is being augmented



(a) (b)

Fig. 1: Liu et al.'s AR interface [4]: (a) The user is able to patch the robot's knowledge structure and (b) The user is able to teach the robot a new action by manipulating the virtual grippers

(human, robot or environment).

Augmented human perception of environment: In Design A's teaching process, the user manipulates the AR model of the gripper in order to teach actions to the robot. This is intended to avoid physical contact between the human and the robot to ensure human safety. However, as the user will be interacting with the virtual model at a distance from the robot, it can be difficult for the user to gauge the alignment of the robot with the environment. This issue could be lessened by using a depth perception system similar to [15]. By using strips of different colours to indicate to the user the different depths around the robot, this could help the human teacher to provide better guidance to the robot.

Augmented human perception of robot: Design A shows the knowledge structure of the robot thereby making the human more aware of what the robot knows. As mentioned in the previous section, we could further augment the human's perception of the robot by simulating the movement of the robot like in [10], [11]. AR could be used to indicate the workspace of the robot like in [16] or the robot's range limit like in [17].

Augmented human perception of self: Currently, during the interaction with the virtual gripper, Design A presents a warning sign to the user if it estimates that the intended pose is out of range. Using [17]'s technique of providing a colour coding to the virtual robot to show to the user when it is out of range, this can also be applied to Design B. Additionally, AR can be used to provide feedback to the user of her/his teaching. This may include demonstration queries [18] from the robot during the teaching process.

Augmented robot perception of environment: In Design A, the user interacts with AR in order to teach the robot what it must know to open medicine bottles. In Design B, the user can, in addition, help the robot to identify how much physical space is available for it to perform the task. A similar function has been implemented before whereby the user can indicate to the robot areas of obstacles [19].

Augmented robot perception of human: In Design A, the robot is able to recognise the human's teachings. However, this can be extended in Design B by having the robot form a model of the specific human's preferences such as when she/he typically wants the bottle/s to be opened and which particular bottle/s.

Augmented robot perception of self: The robot currently recognises what it must learn and what it must do in the original system. An additional functionality could be the ability for the user to give the robot a rating of its performance, similar to how a teacher grades a student's work [20].

IV. Augmentation Artifacts

In previous sections, we speculated high-level potential design ideas for Design B. In this section, we can look into more detail the types of AR artifacts - the last dimension of the taxonomy - to be employed for each of these additional design ideas. This dimension from the taxonomy is comprised of:

- **Augmented Embodiment**: the AR artifact serves as part of the agent
- **Augmented User Interface**: the AR artifact is anchored onto the user's display
- **Augmented Interactive Objects**: AR artifacts that the human or the robot can interact with
- **Augmented Scene**: all other AR artifacts which serve as part of the virtual scene

The following is a summary of the design ideas put forward in the previous sections and the augmentation artifact types which can be used:

1) **Bottle content:** Augmented Scene in the form of text
2) **Amount of bottle content remaining:** Augmented Scene in the form of text and/or a bar diagram
3) **Depth Perception:** Augmented Scene to show the coloured strips for depth awareness
4) **User-specified workspace for the robot:** Augmented Interactive Object as an adjustable 3D bounding box for the user to interact with, and Augmented User Interface for the user to navigate to this mode
5) **Robot's feedback to human's teaching:** Augmented User Interface for the user to navigate to the appropriate mode, and Augmented Scene in the form of text and/or symbols for the human user
6) **Preview robot motion:** Augmented Embodiment for the virtual model of the robot and Augmented Interactive Objects for the virtual models of the medicine bottles.

TABLE II: The new functionalities and their 1) augmentation perception categories, 2) their AR functional roles, and 3) augmentation artifact types which could be used

Functionality	Augmented Perception						Function			Artifact			
	Human			Robot									
	Robot	Environment	Self	Human	Environment	Self	Artificial Timescale	Augmented Comprehension	Augmented Control	Augmented Embodiment	Augmented Interactive Objects	Augmented Scene	Augmented UI
1 Bottle content	○	●	○	○	○	○	○	●	○	○	○	●	○
2 Bottle percentage	○	●	○	○	○	○	○	●	○	○	○	●	○
3 Depth perception	●	●	●	○	○	○	○	●	○	○	○	●	○
4 Robot workspace	●	●	○	○	●	●	○	●	●	○	●	○	●
5 Robot's feedback	●	○	●	○	○	○	○	●	○	○	○	●	●
6 Preview robot plan	●	●	○	○	○	○	●	○	○	●	●	○	○
7 Range indication	●	○	●	○	○	○	●	●	○	●	○	○	○
8 History logs	●	●	○	○	○	○	●	○	○	○	○	○	●
9 Bottle selection	○	●	○	●	●	●	○	○	●	○	●	○	●
10 Auto open	○	○	○	●	●	●	○	○	●	○	●	○	●
11 Alternative controls	○	●	●	●	○	●	○	○	●	○	●	○	●
12 Robot rating	○	●	○	●	●	●	○	○	●	○	○	○	●

●=Yes; ○=No.

7) **Indication that robot is out of range:** Augmented Embodiment as a coloured virtual model of the robot
8) **History logs:** Augmented User Interface for the user to browse through
9) **Bottle selection for opening:** Augmented User Interface for the user to select the bottle selection mode, and Augmented Interactive Objects for the user to interact with the virtual models of the bottles
10) **Set for automatic bottle-opening:** Augmented User Interface to navigate to the appropriate mode and Augmented Interactive Objects as virtual medicine bottle models
11) **Control via tongue drive/eye gaze/other means:** Augmented User Interface and Augmented Interactive Objects for the user to navigate through the menu and interactables
12) **Rating of robot performance:** Augmented User Interface to navigate to the mode and input a rating for the robot

Table II summarises the additional functionalities presented to Design A to acquire Design B. For each of the new functionalities, augmentation artifact types which can be used are listed in the table.

V. Future Research

In this paper, we demonstrated how a recently proposed taxonomy of augmented reality in human-robot interaction can be used to help HRI researchers classify and evaluate AR-HRI systems, and pose future functional design ideas. In particular, we analysed which areas within the taxonomy an existing system already fulfills and suggested potential additions which could be made. We examined the different high-level functional roles AR can serve, the different parts of perception AR can be used to augment in HRI and the types of AR artifacts which could be used accordingly.

Although AR is a relatively new research area with several ongoing challenges [21], it is rising in prevalence and hence it is opportune to study its capabilities and possibilities within HRI. We hope that this demonstration will help future research identify further questions and advance the field.

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