Compatibility and Continuity in Augmented Reality Systems

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ABSTRACT

Integrating virtual information and new action in the real world of the user, is becoming a crucial challenge for the designers of interactive systems. The Augmented Reality (AR) paradigm illustrates this trend. Virtual information or new action are defined by the AR system to facilitate or to enrich the natural way the user would interact with the real environment. We focus on the outputs of such systems, so that additional virtual information is smoothly integrated with the real environment of the user. We characterize the integration of virtual entities with real ones using two new properties: compatibility and continuity. The CASPER system, developed in our teams, is used to illustrate the discussion.

1 INTRODUCTION

One of the recent design goals in Human Computer Interaction has been to extend the sensory-motor capabilities of computer systems to combine the real and the virtual in order to assist users in interacting with their physical environments. In [3], by considering the target operations (i.e., in the real or virtual world), we made a clear distinction between Augmented Reality (AR) and Augmented Virtuality (AV) systems:

- In AR systems, interaction with the real world is augmented by the computer.
- In AV systems, interaction with the computer is augmented by objects and actions in the real world.

In this paper, we focus on AR systems as defined above. Our application domain is Computer Assisted Surgery (interaction with the real world, the patient, enhanced by the computer). We study the output interfaces of AR systems in order to merge virtual entities with real ones. Real environment and real entities are prerequisite for the design of such systems.

The structure of the paper is as follows: We briefly present our notation, called ASUR [4]. The ASUR notation describes an AR system with a user's task-centered point of view. The links between the real world and the virtual world are modeled as adapter components. We then define two ergonomic properties, namely the compatibility and the continuity, and explain how to study them based on an ASUR description of the system. We conclude with an example that illustrates the two properties. This example is based on CASPER a computer assisted surgery system, whose main features are presented in the next section.

2 AN ILLUSTRATIVE EXAMPLE: CASPER

CASPER (Computer ASsisted PERicardial puncture) is a system that we developed for computer assistance in pericardial punctures. The problem is to insert a needle percutaneously in order to access the effusion with perfect control of the needle position and trajectory. The danger involves puncturing anatomical structures such as the liver or the heart itself that may have very severe consequences for the patient. A detailed medical description of the system can be found in [2]. CASPER includes five major steps: acquisition of Ultra Sound images of the heart, segmentation of data, planning, calibration and guidance. Ultra Sound images localized in 3D space are collected before the intervention and are used to model the effusion position and to detect anatomical obstacles at risk. These images are, in this release, manually segmented. From these segmented data, a safe zone for puncture is computed by the system. Planning consists of selecting a target point in that zone and a safe linear trajectory to reach it. Guidance is achieved through use of an optical localizer that tracks the needle position. Prior to this guidance step, calibration procedures are executed pre-operatively in order to calibrate the imaging system and the tool. Figure 1 shows the application in use during the intervention (guidance step).

Figure 1: The CASPER application being used.

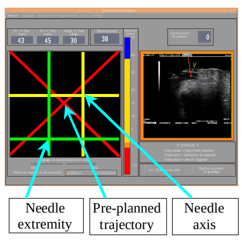

Figure 2: CASPER screen, the guidance information.

The system transforms the signal from the needle localizer into a graphical representation of the position and the orientation of the needle. In the same window on screen, presented in Figure 2, the current position and orientation of the needle are represented by two mobile crosses, while one stationary cross represents the planned trajectory. When the three crosses are superimposed the executed trajectory corresponds to the planned one. On the right side of the window that contains the crosses, a gauge is displayed that translates the current depth of the performed trajectory according to the pre-planned one.

3 ASUR NOTATION

In this paragraph, we briefly present our ASUR notation. ASUR is fully described and illustrated in [4]. In the following paragraph, we will then use an ASUR description of a system to study the compatibility and continuity properties.

ASUR describes an interactive system as a set of four kinds of entities, called components. When applying ASUR, a relation between two components describes an exchange of data. The four components are **A**dapter, **S**ystem, **U**ser and **R**eal objects. The computer system, called System (**S**), is able to store, retrieve and transform data. Objects of the real world may also be used for interaction. We identify two kinds of real objects: a tool used to perform the task (**Rtool**), and the real object of the task (**Rtask**). Finally, in order to link the virtual world (component **S**) with the real world (components **U**, **Rtool** and **Rtask**), e.g. to establish a bridge between virtual and real worlds, we add a fourth component, the adapter (**A**). Obvious examples of adapters are the mouse, the keyboard and the screen. Examples of adapters in Computer Assisted Surgery are ultrasonic or electro-magnetic localizers. We distinguish two types of adapters:

- input adapter (**Ain**), which provide information from the real world (**U**, **Rtool** and **Rtask**) to the system (**S**) including a keyboard and a localizer,
- output adapter (**Aout**), which provides information from the virtual world (**S**) to the real world (**U**, **Rtool** and **Rtask**), including a screen and a mechanical arm to guide a tool.

The four ASUR components are described along the Role axis of our dimension space [5] for the design of interactive systems within their Physical Environments. In our dimension space, an entity's role identifies how the entity contributes (if at all) to the ongoing task. The role axis is not a continuum, but a set of discrete points (Object of the task, Actor, Instrument and Adapter) describing possible roles for the entity. The corresponding function between the ASUR components and the entity's roles of our dimension space is the following one: (**A**dapter=Adapter) (**S**ystem=Actor) (**U**ser=Actor) (**Rtool**=Instrument) (**Rtask**=Object of the task).

An AR system is composed of these four ASUR components which are able to exchange information with each other. In Figure 3, we present the ASUR description of CASPER:

- The surgeon (U) handles and observes a surgical needle (Rtool): **U↔Rtool**.
- An optical localizer (Ain) tracks the needle: **Rtool→Ain**.
- Information captured by the localizer is transmitted to the system (S): **Ain→S**.
- The system then displays the current position and the pre-planned trajectory on a screen (Aout): **S→Aout**.
- The surgeon (U) can therefore perceive the information: **Aout→U**.
- Finally, the object of the task is the patient (Rtask), who is linked to the needle, and perceived by the surgeon (U): **Rtask→U**.

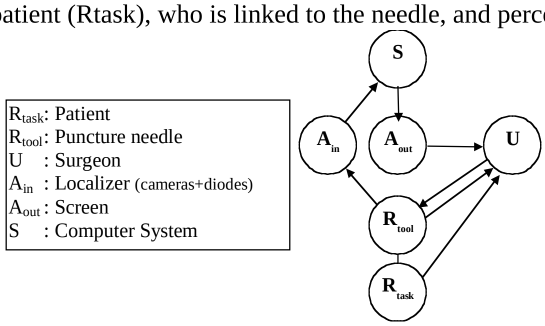

Figure 3: ASUR description of CASPER. Extracted from [4].

4 COMPATIBILITY AND CONTINUITY IN AR SYSTEMS

4.1 Definitions

As explained above, we focus here on the output interfaces of AR systems. The goal is to study how to merge virtual entities with real ones. Real entities, such as the needle and the patient in CASPER, are prerequisite. We based our study on the two ergonomic properties that characterize the output user interface:

- Observability characterizes "the ability of the user to evaluate the internal state of the system from its perceivable representation" [6];
- Honesty characterizes "the ability of the system to ensure that the user will correctly interpret perceived information and that the perceived information is correct with regards to the internal state of the system" [6].

Observability is related to the users' perception while honesty supports users' interpretation. Perception and interpretation processes can be modeled using ICS [1]. Observability and honesty characterize the presentation of one entity at a given time. In order to study the combination of real and virtual entities, it is consequently important to consider the observability and honesty of multiple entities, some are real while others are virtual. To do so, we distinguish multiple representations of different entities from multiple representations of one entity. We define compatibility as the observability and honesty of multiple representations of different entities and we define continuity, as the observability and honesty of multiple representations of one entity. As shown in Figure 4, compatibility and continuity can be applied at both the perceptual and cognitive levels:

- The compatibility at the perceptual level denotes how easy or difficult it is for the user to perceive all the entities of the system at a given time. The compatibility at the cognitive level is assessed in terms of the cognitive processes [1] involved in the interpretation of all the entities perceived. As shown in Figure 4, the compatibility property at the perceptual level as well as at cognitive level implies respectively the observability and honesty of the representation of each entity.
- Perceptual continuity is verified if the user directly and smoothly perceives the different representations of a given entity. Cognitive continuity is verified if the cognitive processes that are involved in the interpretation of the different perceived representations are similar. If not the user will have difficulties to obtain a unique interpretation of the entity resulting from the combination of the interpreted perceived representations. As for compatibility, the continuity property at the perceptual level as well as at cognitive level implies respectively the observability and honesty of each representation of the entity.

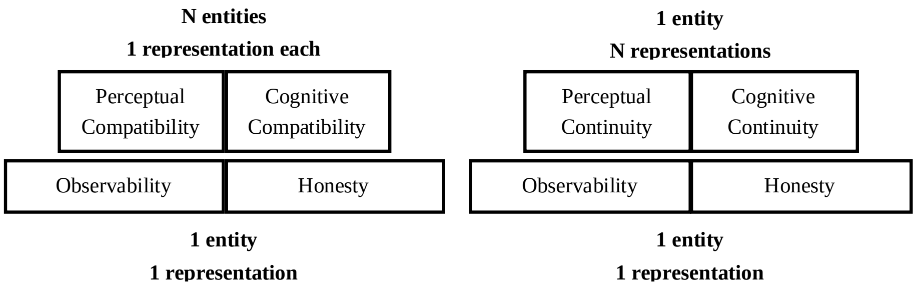

Figure 4: Ergonomic properties: observability, honesty, compatibility and continuity.

4.2 ASUR based analysis of compatibility and continuity

Based on an ASUR description of an AR system, the compatibility and continuity properties are studied by focusing on all the relations arriving to the User (**U**). We distinguish:

- relations from the computerized part (**S**) to the user (**U**) via an adapter (**Aout**),
- relations from the real world (**Rtool** and **Rtask**) to the user (**U**).

For each of these relations arriving to the user, we define the perceptual environment and interaction language.

4.2.1 Perceptual environment and interaction language

For each ASUR relation arriving to the user, we first study the perceptual environment. The perceptual environment is linked to the human sense involved to perceive the information along this relation. In addition a perceptual environment is also defined by the spatial location at which the user must focus to obtain information. We consequently define a perceptual environment as the coupling of a human sense s with a location l: <s, l>. The perceptual environment is defined by the component source of the ASUR relation and therefore characterizes output adapters (Aout) as well as real objects (Rtool and Rtask).

We then consider the cognitive processes involved to interpret the information perceived along an ASUR relation arriving to the user. We characterize these processes in terms of the interaction languages used to express data carried by the relation. As opposed to a perceptual environment, that characterizes an adapter or a real object, several interaction languages can be involved for one relation. For example, the relation Aout→U of Figure 3 involves different interaction languages and consequently cognitive processes: one for the cross-based representation and one for the gauge.

The perceptual environment and the interaction language are two characteristics that enable us to study compatibility and continuity respectively at the perceptual level and cognitive level. The perceptual environment characterizes the component source of the relation (Aout, Rtool or Rtask), while the interaction language describes the relation itself. The two characteristics (perceptual environment, interaction language) can be related to our definition of an interaction modality being defined as the coupling of a device with an interaction language [7]: the perceptual environment therefore describes the device of a modality. As a consequence we study the different interaction modalities that are related to virtual entities (from the system) as well as to real entities: AR systems are then studied as multimodal systems [7].

4.2.2 Compatibility and continuity studied within an ASUR description of a system

By studying all the relations arriving to the user and their corresponding perceptual environments and interaction language, the compatibility can be assessed. Too many relations with different perceptual environments and interaction languages directly translate a risk of overloading and consequently potential errors because the user will not be able to perceive and interpret all the entities that are relevant for performing her/his task.

Continuity assessment is based on the study of relations arriving to the user that are vehicles of the same entity. The user must combine information along these relations in order to mentally represent the entity. Fusion at the perceptual and cognitive levels has been studied in the general cognitive architecture ICS [1].

- At the perceptual level, incompatibility and discontinuity are defined between the involved perceptual environments, a perceptual environment being defined as the coupling of a human sense s with a location l. Because it has been shown that the user can perceive several pieces of information along one perceptual canal s (for example several sounds at the same time), incompatibility and discontinuity are mainly due to different locations of the various perceptual environments.
  During the design, incompatibility and discontinuity at the perceptual level are directly related to the choice of output adapters. Indeed real entities are prerequisite for the design of such systems. Output adapters must be selected according to their perceptual environments: these environments must be in accord with the ones associated with the real objects involved in the interaction.
- At the cognitive level, incompatibility and discontinuity are defined as the difference between the interaction languages associated with the relations.
  During the design, incompatibility and discontinuity at the cognitive level are directly related to the choice of interaction languages used by the system to convey virtual entities. Such interaction languages must be in accord with the ones linked to the interpretation processes of the real objects involved in the interaction.

In the following paragraph we illustrate the study of continuity within an ASUR description of CASPER

5 COMPATIBILITY AND CONTINUITY IN CASPER

5.1 First version of CASPER

We study here the continuity at the perceptual and cognitive levels based on the ASUR description of the CASPER system of Figure 3. To study the continuity property, we consider the action of puncturing in CASPER and we focus on the needle: the real one and the one represented on screen (representation multiplicity). The two ASUR relations Aout (screen)→U and Rtool (needle)→U are both vehicles of the same entity: the needle.

At the perceptual level, the two relations Aout (screen)→U and Rtool (needle)→U have incompatible perceptual environments. The surgeon has to look both at the real needle to avoid any distortion of the tool and at the screen to get the guiding information (represented as a stationary cross) according to the virtual needle (represented as two mobile crosses). Keeping the trajectory aligned and controlling the depth of the needle by referring to the visual display was found difficult to do. The required switch between the screen and the operating field was disturbing to the surgeon. Risks of error occur due to the necessity of looking somewhere else than on the operating field. Perceptual continuity is not verified here.

Likewise, at the cognitive level, the two cognitive processes associated with the interaction languages are very different. Indeed, the representation of the needle on screen (the two mobile crosses) is bi-dimensional, while the position of the real needle is of course three-dimensional. The surgeon must always shift between the 3-D position of the needle and the cross-based graphical representation on screen. The matching between the real object and its representation is far from direct. Cognitive continuity is transgressed.

5.2 Redesign of CASPER

We redesign our CASPER application in order to address the dual sources of errors due to discontinuity at the perceptual and cognitive levels.

We developed a new version of CASPER using a see-through Head Mounted Display (HMD). The see-through HMD eliminates the problem of perceptual continuity: the surgeon can see the operating field through the HMD (patient and needle) as well as the virtual needle and the guidance data in the same location.

But even if we modify CASPER to display the cross-based representation on a see-through HMD, continuity at the cognitive level is still transgressed. We therefore decided not to virtually represent the needle because the real one is directly available in the unique perceptual environment, the operating field through the HMD. The problem therefore shifts from a cognitive continuity problem to a cognitive compatibility problem between the real needle and the virtual planned trajectory. The two entities are crucial for the action of puncturing. To address the cognitive incompatibility, we have adopted a cone representation to visualize the trajectory (3D representation as the real needle). Figure 5 presents a view through the HMD under experimental conditions. We have performed usability experiments with the help of colleagues of the Experimental Psychology laboratory of the University of Grenoble. Different settings were defined according to the device (screen or HMD) and the representation of the trajectory (cross-based representation or 3D cone). The data are currently being processed. Nevertheless we have already observed a general improvement when using the HMD as compared to the screen, regardless of the representation of the trajectory.

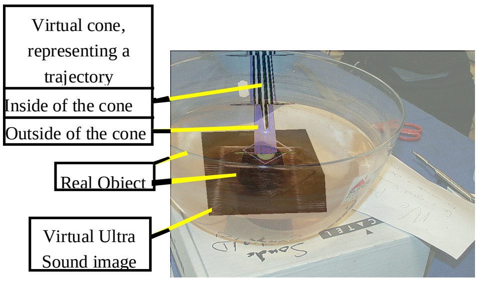

Figure 5: A view through the HMD merging real objects with a virtual conic trajectory. Extracted from [4].

6 CONCLUSION

In this paper, we have defined two properties, the compatibility and the continuity, in order to characterize the merging of virtual entities with real ones. We showed how to study them within an ASUR description of a system. We illustrate the approach using our CASPER system. Although the properties can be studied without the ASUR notation, we believe that the ASUR notation provides a support for systematically studying the two properties by defining the real and virtual entities and their relationships involved in the interaction.

During the workshop, we propose to discuss the definition of the two properties, compatibility and continuity, both at the perceptual and cognitive levels, in relation to the known properties of observability and honesty. In addition we established a link between Augmented Reality systems and Multimodal ones: merging virtual entities with real ones corresponds to the problem of combining two interaction modalities, one linked to the virtual entity and one to the real entity. Because multimodal systems have been more studied than AR systems, such an association is interesting to consider. Can we apply the results of multimodal systems to AR systems? The first step would be to characterize the perception and interpretation of real objects, as we did for virtual entities in terms of modalities (a modality being defined as the coupling of a device with an interaction language). In this paper, we adopted this multimodal point of view and we studied the perception and interpretation of real and virtual entities related to a given task in terms of the perceptual environment (characterization of the device, first component of a modality) and the language (second component of a modality). Finally the paper raises the problem of the definition of a physical environment. In the paper we describe the physical environment in terms of the physical entities involved in the interaction: the tools used to perform the task (Rtool), the real objects of the task (Rtask) and the adapters (A) to establish a bridge between virtual and real worlds. During the design of AR systems, do we need to identify other real entities and therefore extend the definition of the physical environment?

7 REFERENCES

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