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Classification Space for Augmented Surgery, an Augmented Reality Case Study

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ABSTRACT 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 the user in his environment. Such systems are called Augmented Reality (AR). Although AR systems are becoming more prevalent we still do not have a clear understanding of this interaction paradigm. In this paper we propose OPAS as a generic framework for classifying existing AR systems. Computer Assisted Medical Interventions (CAMI), for which the added value of AR has been demonstrated by experience, are discussed in light of OPAS. We illustrate OPAS using our system, CASPER (Computer ASsisted PERicardial puncture), a CAMI system which assists in surgical procedures (pericardial punctures).

KEYWORDS: Augmented Surgery, CAMI, Augmented Reality, Classification Space

1. INTRODUCTION

The term "Augmented Reality" (AR) appears in the literature usually in conjunction with the term "Virtual Reality" (VR). The difference between AR and VR involves the "immersiveness" of the system. A VR system strives for a totally immersive virtual environment in which the user is performing his task. In contrast, an AR system combines the real and the virtual in order to assist the user in performing his task in a physical setting.

In recent years, Augmented Reality (AR) has been the subject of growing interest. However, there is currently no consensus either on a precise definition of AR or on a design space (Milgram & Kishino, 1994). Within this context, it is therefore difficult to compare the existing AR systems and explore new designs. In this paper we present a classification space, OP-a-S, to provide a systematic classification process of augmented reality systems.

Our approach draws from the study of Computer Assisted Medical Intervention (CAMI) systems and augmented reality systems. The next section describes CAMI systems and their goals. We then describe the components of our classification space OP-a-S and illustrate it using our system CASPER (Computer ASsisted PERicardial punctures). In the final section, we use the notion of adapters between the real and the virtual to show how OPAS allows us to classify existing AR systems.

2. COMPUTER ASSISTED MEDICAL INTERVENTIONS (CAMI)

There are many application domains of Augmented Reality (AR), including construction, architecture (Webster et al., 1996) and surgery (Bainville et al., 1995, Cinquin et al., 1995, Taylor et al., 1992). The variety of application domains makes it difficult to arrive at a consensus definition of AR: i.e. different people, having distinct goals are using the term "Augmented Reality". Our application domain is the augmented surgery or CAMI systems. The main objective of CAMI systems is to help a surgeon in defining and executing an optimal surgical strategy based on a variety of multi-modal data inputs. The objectives aim at improving the quality of the interventions by making them easier, more accurate, and more intimately linked to pre-operative simulations where accurate objectives can be defined. In particular, one basic challenge is to guide a surgical tool according to a pre-planned strategy: To do so robots and 3D localizers (mechanical arms or optical sensors) perform real time tracking of surgical tools such as drills (Cinquin et al., 1995).

Augmented reality plays a central role in this domain because the key point of CAMI systems is to "augment" the physical world of the surgeon (the operating theater, the patient, the tools etc.), by providing pre-operative information including the pre-planned strategy. Information is transmitted between the real world and the computer world using different means: computer screens, mouse, pedals, tracking mechanisms, robots, etc.

Since 1985, the TIMC laboratory is working on designing, developing and evaluating CAMI systems. Through progress of technology and growing consciousness of the possibilities of real clinical improvements with computers (Taylor et al., 1992), augmented reality systems are now entering many surgical specialties. Such systems can take on the most varied forms (Bainville et al., 1995). Three classes of CAMI systems are identified in (Troccaz et al., 1997): (1) The passive systems allow the surgeon to compare the executed strategy with the planned one. (2) The active systems perform subtasks of the strategy with the help of an autonomous robotic system. (3) The semi-active or synergistic systems materialize the surgical strategy but the surgeon is in charge of its execution. The system and the surgeon are working in a synergistic way. At Grenoble, three golden rules have guided the CAMI project for about 14 years:

- R1: Design systems for which the clinical value is well defined.
- R2: Develop generic systems that can be applied to different clinical applications.
- R3: Provide effective collaboration between the surgeon and the system through efficient interfaces.

Our approach in designing CAMI systems, based on these three rules, encompasses three domains:

- Medical domain and clinical requirements
- Safety critical systems
- Human Computer Interaction.

In this paper we focus on the interaction between the surgeon and the computer (Rule R3). As pointed out during the CHI'98 panel (Cobble, 1998) on HCI in Health Care, user-centered design can play a central role in designing CAMI systems. Indeed CAMI systems are numerous in many different surgical specialties but the most attention has been paid to the technical issues related to image processing, data fusion and surgeon assistance stemming from the clinical specifications of the problem. Very little effort has been applied to modeling the interaction between the surgeon and the system. The design approach of this clinically-oriented CAMI project so far has been technology-driven. Such a technology driven approach also characterizes AR systems in general. As a proof, let us consider the technology driven definition of AR quoted in (Milgram & Kishino, 1994) concerning a session in a conference: "a form of virtual reality where the participant's head-mounted display is transparent, allowing a clear view of the real world". Nevertheless, augmenting the reality of a user may also rely on the use of force or aural feedback, which is not reflected by Milgram's definition. We adopt here a complementary user-centered approach providing a user-centered classification space for augmented reality systems.

3. THE OPAS CLASSIFICTAION SPACE

Our classification space, OPAS, is dedicated to interactive systems including AR ones. We first explain the four components of OP-a-S and their relationships. We then consider the target of the tasks supported by the system and the type of augmentation. Finally we demonstrate how to apply OP-a-S using our system CASPER.

3.1 Four components

We model the interaction between the user and an interactive system by identifying four components: **O**bject, **P**erson, **A**dapter and **S**ystem (OP-a-S).

The computerized component of the system, called System (S), is able to store, retrieve and transform data. The real object (O) including a drill, a pen or a sheet of paper is manipulated by the user or a robot in order to perform the task. The Object component may include human beings provided that they are involved in the process without interacting directly with the system. This is the case of the patient for example in a CAMI system. The person (P) uses the system. The user (P) and the object (O) belong to the real world ("atom world") while the system component (S) belongs to the virtual or synthetic world ("bit world"). In order to establish a bridge between these two worlds, we introduce a fourth component called Adapter (A). Obvious examples of adapters are the mouse, the keyboard and the screen. Examples of adapters in CAMI systems are ultrasonic or electro-magnetic localizers. In Embodied User Interfaces (i.e., the user uses a computational device by physically manipulating the device), adapters are pressure sensors or tilt sensors (Fishkin, et al., 1998).

The four components of OPAS are clearly defined above. The main difficulty is to distinguish between adapters (A) and objects (O). For example, in the most common case, a mouse is an adapter because a mouse is dedicated to transforming physical movements of the user to movements in the virtual world displayed on screen. But if the user employs the mouse as a paperweight, the mouse then becomes an object.

3.2 Links between the components

The interactive system is composed of these four components which are also able to exchange information with each other. Exchange of data is uni-directional and represented on OP-a-S diagrams with an arrow, from the source-component to the destination-component of the system. An example is the flow of data from the surgical tool (O) to a localizer (A) in a CAMI system, where the localizer (A) performs the tracking of the surgical tool (O):

O (Surgic l tool) ⟶ **A** (Loc iz ar)

Data flow

An adapter according to our definition allows flow of data:

- between the adapter and the system component (S, "bit world"), and
- between the adapter and the user or the object (P or O, "atom world").

3.3 Target of the tasks

Because two worlds "atom" and "bit" belong to OPAS modeling, it is important to specify if the system’s user is performing a task in order to modify the real world or in order to modify the state of information maintained by the computer. One may thus consider P's task in terms of target operations in:

- real world (human-real world interaction), and
- computer (human-computer interaction).

For example in CAMI systems the target is mainly the real world (performance of the medical intervention) and, in clinical information systems the target is the computer (modification of the state of medical records). The two possible targets of the user’s task, real world and computer, respectively correspond to the two terms presented in (Milgram & Kishino, 1994): "Augmented Reality" (AR) and "Augmented Virtuality" (AV). Reality designates the real world of the user while virtuality corresponds to the virtual world created by the computer. Applying the two concepts to characterize interaction we obtain:

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

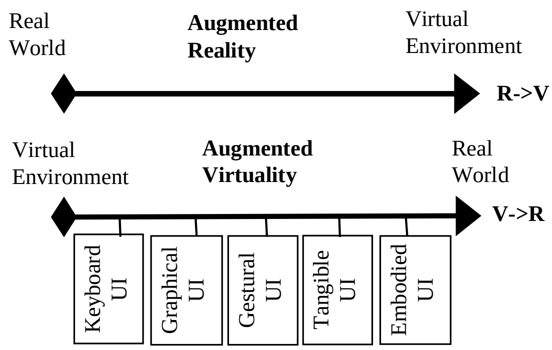

Figure 1: Two parallel continua for characterizing interaction, based on the Reality-Virtuality continuum (Milgram & Kishino, 1994). Along the V->R (Virtuality->Reality) continuum, we position the different interaction paradigms presented in (Fishkin, et al., 1998).

In (Milgram & Kishino, 1994) the two concepts AR and AV are presented as belonging to the Reality-Virtuality continuum in order to classify displays. Yet characterizing interaction requires us to distinguish two parallel continua as presented in Figure 1: AR and AV applied to interaction will never meet at a point because the target of the user's task is different. This is because the R->V continuum of Figure 1 is dedicated to human-real world interaction while the V->R continuum characterizes human-computer interaction.

3.4 Type of augmentation

The augmentation provided by the system can take on a number of different forms. For example, using an AR system (target of the task = real world), the user's action (performance) in the augmented real world and/or the user's perception of the augmented real world can be enhanced. If we refer to the Theory of Action (Norman, 1986), augmentation can be dedicated to the execution phase and/or to the evaluation phase. As shown in Figure 2, the two types of augmentation [execution and evaluation] are applied to the two types of target of the tasks [real world (AR) and computer (AV)]. We illustrate this last point in the next two subsections.

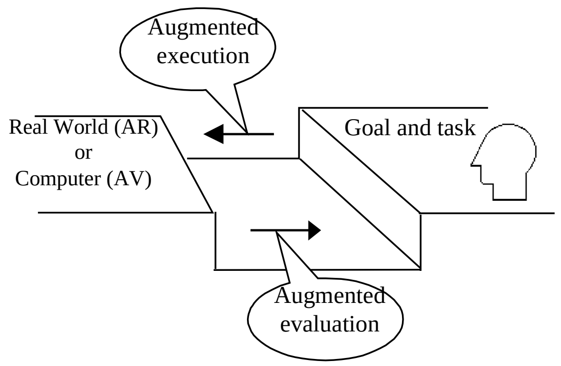

Figure 2: Two types of augmentation: augmented execution and/or augmented evaluation applied to Augmented Reality (Target of the task = Real World) and Augmented Virtuality (Target of the task = Computer).

3.4.1 Augmented reality

For example, the DigitalDesk (Wellner, 1993) is an AR system that enables the user to cut and paste drawings made on real paper using real pens. Such action is not directly possible in the real world: the execution phase is augmented by the computer. Likewise, a system that automatically opens the door when a person wearing an active badge (Want et al, 1992) appears in front of it is also a case of an augmented execution phase: The same task in the real world (open the door) would not be executed the same way.

As opposed to the active badge, the NaviCam system (Rekimoto & Katashi, 1995) is an AR system that augments the evaluation phase. NaviCam displays situation sensitive information by superimposing messages on its video see-through screen. For example one application is the augmented museum: the visitor is looking at a picture while obtaining a textual description of it on screen. Another example of augmented evaluation, which is not visual, is the Audio Aura system. The Audio Aura system (Mynatt et al, 1998) provides information, via background auditory cues, that is tied to the user's physical actions in the workplace. For example, when a visitor discovers an empty office, in Audio Aura he hears auditory cues that convey whether a person has left his office a long time ago or if the visitor has just missed him. Other scenarios presented in (Mynatt et al, 1998), such as hearing a cue that conveys the number of email messages received while entering the coffee room, are not examples of augmented reality but examples of augmented virtuality because the target of the task is the computer. Augmented virtuality is the topic of the next subsection.

AR	Augmented execution	- DigitalDesk - Active badge: open a door
	Augmented evaluation	- NaviCam Augmented museum - Audio Aura

3.4.2 Augmented virtuality

Examples of augmented execution in human-computer interaction involve input modalities (Nigay & Coutaz, 1995) based on real objects, such as Fitzmaurice et al's bricks or Ishii & Ulmer's phicons (Fitzmaurice et al, 1995; Ishii & Ulmer, 1997). Ishii has described this interaction paradigm as the Tangible User Interface. Another example of augmented execution is defined by the more recent approach called Embodied User Interface (Fishkin, et al., 1998): the user executes tasks with the computer by physically manipulating the computer.

Examples of augmented evaluation in human-computer interaction refer to more realistic graphics on screen and to output modalities that mimic the real world feedback (visual, audio and tactile feedback).

AV	Augmented execution	- Tangible UI: Bricks, Phicons. - Embodied UI
	Augmented evaluation	- Realistic graphics - Tactile feedback, etc.

In both cases (AR and AV), a system may augment the execution and the evaluation phases.

For example, the DigitalDesk augments the execution phase because of the copy/paste service it supports, and also the evaluation phase by mixing real drawings made on real paper with displayed graphics.

3.5 OPAS modeling of CASPER

We describe here the OPAS modeling of our CASPER application developed in collaboration with the Grenoble University Hospital. The clinical problem is to remove a build up of fluid (water, blood) in the region around the heart (pericardium), the effect of which is to compress the heart. This procedure is performed through minimal access to the chest. CASPER (Computer ASsisted PERicardial punctures) allows the pre-operative acquisition and modeling of a 3D stable region in the pericardial effusion from which a target is selected and a safe trajectory is planned. The success of the planned strategy for a surgery is markedly enhanced by on screen guidelines available to the surgeon. Indeed, as shown in Figure 3, CASPER assists the surgeon by providing in real time the position of the puncture needle according to the planned strategy. The user interface of CASPER has been designed by a multidisciplinary team including a surgeon and is fully described in (Chavanon et al., 97). Figure 3 shows also the components of CASPER in use.

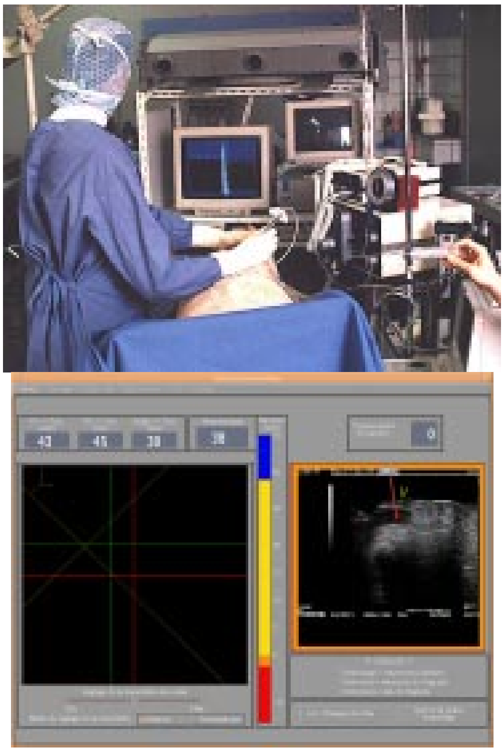

Figure 3: The CASPER application in action.

An OP-a-S description is as follows. The System component (S) 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, 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. Two adapters (A1, A2) are necessary: The first one (A1) is the screen for displaying guidance to the surgeon, and the second one (A2) is dedicated to tracking the needle position and orientation. The latter is composed of diodes firmly fixed on the needle and three cameras mounted on a rigid bar. The objects (O) involved in the task are the puncture needle and the patient. Because the surgeon is handling the needle, there is a link from the surgeon (P) to the needle (O) and vice-versa (tactile feedback) (Figure 4). Finally CASPER is a CAMI system and therefore the task's target is the real world (pericardial puncture). In addition CASPER augments the reality of the surgeon by providing pre-operative information during the intervention: CASPER therefore augments the evaluation phase within the surgeon-real world interaction. Indeed the surgeon is still executing the puncture using a needle.

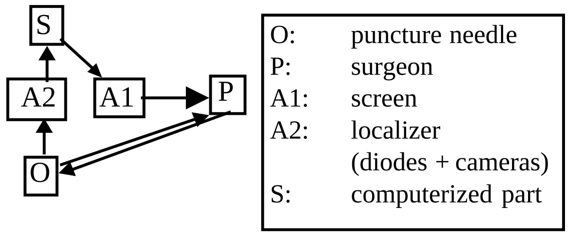

Figure 4: OPAS modeling of CASPER.

So far we have presented and illustrated our OPAS classification space, and by doing so we have defined an Augmented Reality (AR) system as a system that enables the user to perform tasks that have their target in the real world (target of the task = real world). We now focus on the Adapters in AR systems. In particular we study the ergonomic property of continuity in OPAS.

4. ADAPTER: BOUNDARY BETWEEN THE REAL AND THE VIRTUAL

Adapters are the key component of OP-a-S because they establish a bridge between the real and the virtual world. Adapters determine the type of boundaries between the two worlds that in turn characterize the AR systems.

If we adopt a System-centered view, we distinguish Input Adapters (IA) (inputs to the System component) from Output Adapters (OA) (outputs from the System component):

IA ⟶ S **S ⟶ OA**

For example a keyboard or a pressure sensor are input adapters while a screen, a projector or a head-mounted display (HMD) are output adapters.

In addition matching input/output adapters can provide continuity in task achievement: no shift between the real and the virtual worlds is necessary to perform the task. We identify two concepts that are relevant for continuity: action/perception and cognition. Action/Perception and cognition represent two levels of abstraction. Continuity can be defined at the action/perception level or at the cognitive level:

- No action/perceptual gap between the real and the virtual world.
- No cognitive gap between the real world and the representation defined by the virtual world.

For example in CASPER, the screen is an OA that does not provide continuity:

- At the action/perception level, the surgeon must always shift between looking at the screen and looking at the patient and the needle.
- At the cognitive level, the surgeon must always shift between the position of the needle and the cross-based graphical representation on screen.

In this way, OP-a-S shows that at both levels of abstraction, CASPER's screen is a Discontinuous Output Adapter (DOA). Even if we modify CASPER to display the cross-based representation on a see-through HMD, the HMD still does not provide continuity at the cognitive level and is therefore a DOA. Now consider DigitalDesk from an OP-a-S perspective. As opposed to CASPER, the DigitalDesk includes an OA, that is a projector that provides continuity (COA), as modeled in Figure 5. Indeed the DigitalDesk user can draw on real papers on which information can also be displayed via the projector. In addition the Input Adapter in the DigitalDesk is a camera on top of the desk that recognizes the user’s gestures: the camera is a Continuous Input Adapter (CIA). Indeed there is continuity both at the action level (actions are performed at the same place on the same object) and at the cognitive level (same actions as in reality). In CASPER the localizer also serves as a Continuous Input Adapter (CIA): no modification of the actions of the surgeon. To conclude the main difference between CASPER and DigitalDesk is that one Output Adapter is continuous (DigitalDesk, Figure 5) while the other one is discontinuous (CASPER, Adapter A1, Figure 4). Moreover, OP-a-S establishes that CASPER and the DigitalDesk are different not only because of the domain but because of the kind of interaction induced.

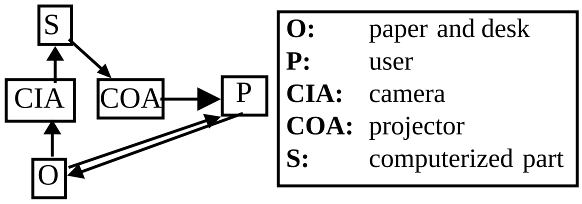

Figure 5: OPAS modeling of the DigitalDesk.

5. CONCLUSION

This paper introduces our interaction-centered approach for classifying Augmented Reality/Virtuality systems. We have presented a conceptual framework, OPAS, in which to place the various aspects of interaction of augmented reality systems as well as augmented virtuality systems. For CAMI systems, OPAS enables us to differentiate between systems that previously all belonged to the passive CAMI systems class (Troccaz et al, 1997). More generally, for augmented reality/virtuality systems, the ability of OPAS to classify existing systems has great promise, especially in light of the rapid technological progress that we are experiencing.

By identifying and organizing the various aspects of interaction, our framework should also help the designer to address the right design questions and to envision future systems. Our goal is to establish a complete interaction-centered design space for AR systems and more specifically CAMI systems. To do so, further work primarily involves linking ergonomic criteria and OPAS modeling in order to identify design principles.

We are currently developing a version of CASPER that represents the trajectory in the form of a cone on a head-mounted display in order to address the discontinuity problem in the current version.

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