A Dimension Space for the Design of Interactive Systems within their Physical Environments

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ABSTRACT

This paper introduces a Dimension Space describing the entities making up richly interactive systems. The Dimension Space is intended to help designers understand both the physical and virtual entities from which their systems are built, and the tradeoffs involved in both the design of the entities themselves and of the combination of these entities in a physical space. Entities are described from the point of view of a person carrying out a task at a particular time, in terms of their attention received, role, manifestation, input and output capacity and informational density. The Dimension Space is applied to two new systems developed at Grenoble, exposing design tradeoffs and design rules for richly interactive systems.

Keywords

Dimension space, interactive system design, groupware, augmented reality

1. INTRODUCTION

Recent years have seen technological advances allowing the exploration of exciting new interaction paradigms that involve, for example, augmented reality and cooperative work. These advances have included the development of inexpensive and novel I/O devices such as cameras, digital sensors, data projectors and immersive displays, the creation of portable devices such as personal digital assistants and portable telephones, and the proliferation of high-speed networks. Examples of richly interactive applications based on these novel technologies include augmented reality flight strips supporting the work of air traffic controllers [17], Ishii's tangible bits [16], embodied interfaces [11], the INFOTABLE and INFOWALL "spatially continuous" workspaces [24], the Magic Board augmented reality whiteboard [9,2,26] and the CASPER computer aided surgery system [10,7].

The common aspect of these applications, and the source of their richness in interaction, is that they blur the line between the computer and the physical world [1]. The design of such systems cannot be limited to the design of a user interface, but extends to the design of how physical and virtual entities are to be combined into a complete system. For example, the design of Mackay's flight strips was informed by ethnographic studies of air traffic controllers, including extensive considerations of how these controllers cooperate amongst themselves, and of the physical design of their workstations.

Up to now, little methodical support has been provided for the design of systems involving multiple actors interacting with both physical and virtual entities in order to carry out some task. Based on the experience at Grenoble in the design and implementation of the CASPER and Magic Board systems, we propose a Dimension Space to aid in the design of complete interactive systems. We consider interactive systems to be made up of entities, both physical and virtual, which may be objects of some task, instruments used in carrying out the task, collaborating actors, or adapters between the physical and virtual worlds [10].

The Dimension Space sets out to identify the properties of these entities, illustrating and contrasting the points of view of actors using the system to carry out a task. Its primary role is to serve as a descriptive and exploratory tool for designers and to communicate and record their reasoning about potential interactive systems. The Dimension Space presupposes an existing and detailed analysis of the content and context of the work domain from which evaluation criteria may be drawn [4,23]. It is capable of describing the interactive properties of combinations of entities, properties that may be of value or disruptive depending on the system of work concerned. The Dimension Space thus belongs to a family of approaches that have been described as *Design Space Analysis* [20], by elaborating possible designs against a determined set of requirements.

The Dimension Space characterizes entities in terms of their attention received, role, manifestation, I/O capacities and informational density. Using the axes of the Dimension Space, we can ask questions such as, what is the purpose of the entity (from the point of view of a user carrying out some task); how does the entity combine physical and virtual attributes, and how does the entity constrain the use of other entities? As is shown in the final section of the paper, the Dimension Space allows us to propose examples of general design rules for richly interactive systems, and helps in evaluating such rules.

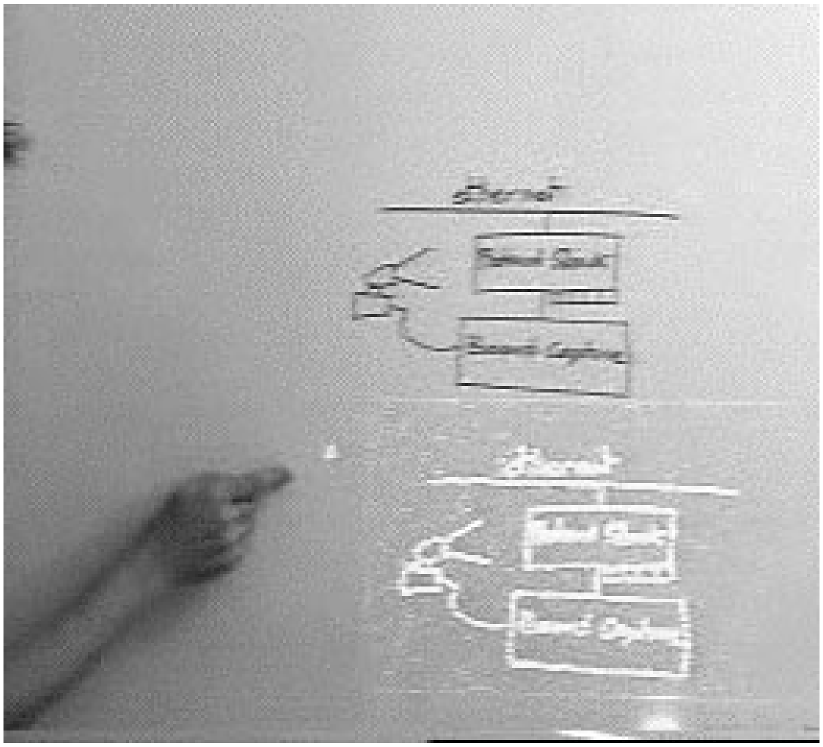

Figure 1: The Magic Board: copying a physical drawing and pasting a virtual one.

The choice of axes over which the Dimension Space is composed was motivated by our experience with the design and use of the CASPER and Magic Board applications. Validation of the Dimension Space is continuing, based on its use in analyzing these and other applications.

This paper is organized as follows. We first introduce CASPER and the Magic Board, which will be used throughout the paper to illustrate the novel design issues of richly interactive systems. We then discuss design questions that arise in such systems, motivating the need for the Dimension Space. Following this, we introduce the Dimension Space itself, and illustrate it with examples. Finally, we discuss how analysis with the Dimension Space can fit within a design process, complementing existing techniques such as task analysis [25], QOC [19] and OPAS [10].

2. EXAMPLE APPLICATIONS

Throughout this paper, we draw examples from two interactive systems: the *Magic Board* augmented reality whiteboard [9] (figure 1), and the *CASPER* computer-aided surgery system [7, 10] (figure 2). These systems have both been implemented, and provide realistic examples of modern user interfaces involving group cooperation and rich interaction between the physical and virtual worlds. We now briefly describe these systems.

- The *Magic Board* is an augmented reality whiteboard. Users may create and manipulate text and graphics that are either physical (using standard dry-ink pens) or virtual (projected via a data projector). The contents of the Magic Board are digitized via a camera. Users may perform operations such as copy/pasting, moving or deleting the virtual contents of the whiteboard, as well as using familiar pens and eraser brushes on the physical content of the board. For example [26], to move a region of the Magic Board, a user performs a sequence of gestures to select a region with his/her finger, and then drags the selection to a new location. As shown in figure 1, the camera is used to track the user's finger. The effect of user actions on the Magic Board depends on whether the content is physical or virtual. For example, this move operation moves virtual drawings but copies physical drawings. Similarly, erasing with a physical brush affects only physical drawings.
- CASPER is an augmented reality system helping surgeons to carry out pericardial puncture operations. The goal of a pericardial puncture procedure is to remove excess fluid (or *effusion*) from the region between the heart and pericardium (an envelope around the heart). The surgeon uses a minimal chest access to convey a needle to this effusion, allowing it to be removed. The needle is guided according to a planned trajectory, based on ultrasound images of the heart. Using CASPER, the surgeon receives real-time information showing the current position of the needle with respect to the planned trajectory. A *localizer*, comprising a camera and a set of diodes attached to the needle, tracks the current position of the needle. As shown in figure 2, a computer display shows a representation of the needle's current position inside the body, in terms of the planned trajectory. The computed representation is based on the position of the outside part of the needle as reported by the localizer. The surgeon therefore can use the computer display to detect and correct errors in the path followed by the needle. In performing the surgical intervention, the surgeon interacts with both physical objects (the needle) and virtual objects (the visualization of the needle trajectory.)

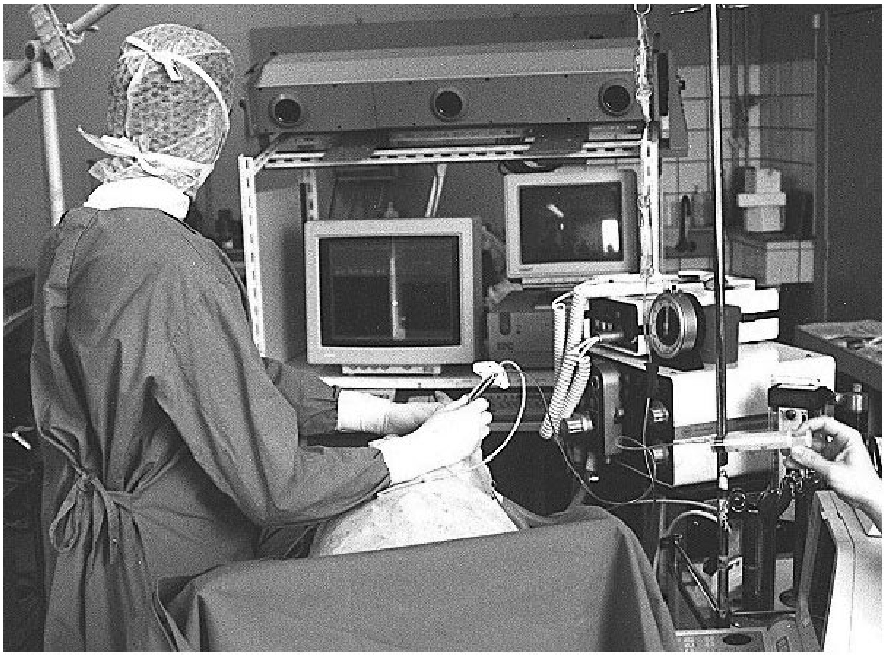

Figure 2: The CASPER system in use in an experimental pericardial puncture operation. The surgeon is examining a visualization of the needle's position with respect to a planned trajectory.

3. RATIONALE

Systems such as those described in the last section involve multiple people collaborating to perform a task, using both physical and virtual artifacts. Traditional interactive systems have been designed as isolated software components, in the context of supporting a single user carrying out some task. Even the designs of applications supporting collaboration often abstract the notion of collaboration away from its physical context, while attempting to preserve its social and organizational setting. In contrast, richly interactive applications must be designed as complete systems involving the mutual interaction of people, software, and physical entities. That is, they must recognize the physical context of collaboration as an active constituent of interactive processes.

Considering the system as a whole exposes problems in both the *static* design of the system, and in the analysis of its *runtime* implications. As we shall see in the next section, the Dimension Space is proposed to expose a broad set of design issues in both the static and runtime design of interactive systems.

Static design issues for systems involving multiple users in a physical setting include:

- *Identifying relevant entities:* A first step in designing an interactive system is to identify the entities from which the system is composed. For example, the entities making up the CASPER system include a needle, a localizer, a visualization of the needle's position, the patient, the surgeon and nurses.
- *Identifying how entities are used:* Just as it is important to design how software entities are used by people in carrying out their tasks, such analysis must extend to physical entities involved in interactions.
- *Identifying tradeoffs in entity choice:* Some entities involved in an interaction are *fixed*, in the sense that they cannot be replaced. (E.g., in CASPER, the surgeon, the patient and the needle are fixed.) Other entities are *replaceable* (e.g., the localizer and the visualization), and can be chosen or designed following analysis of their existing or desired properties. For example, different localizer technologies are available for the CASPER system; in the Magic Board, different technologies are available for digitizing drawings (such as computer vision or tactile input devices.) It is important to identify what tradeoffs are involved in the choice of which replaceable entities to include in the system.

In addition to these static design concerns, design issues arise in the runtime use of the system, both in determining the system's intended use and in identifying problem areas in this use:

- *Use over time:* The attributes of entities within an interaction change over time. This allows the recording of high-level scenarios of work using a mixed physical/ virtual system.
- *Point of view:* Different actors collaborating to perform a task will view the entities making up the system in different ways, depending on their role in the task, their focus of attention, and even on the physical layout of their workspace. The appropriateness of a given entity depends on its multiple-role potential within the "cognitive system" network [15].
- *Identifying discontinuity:* Temporal views of systems help in identifying discontinuities in interaction with the system. Such discontinuities may occur when, for example, different entities compete for an actor's attention, or the attributes of an entity abruptly change as an actor moves from one task to another.

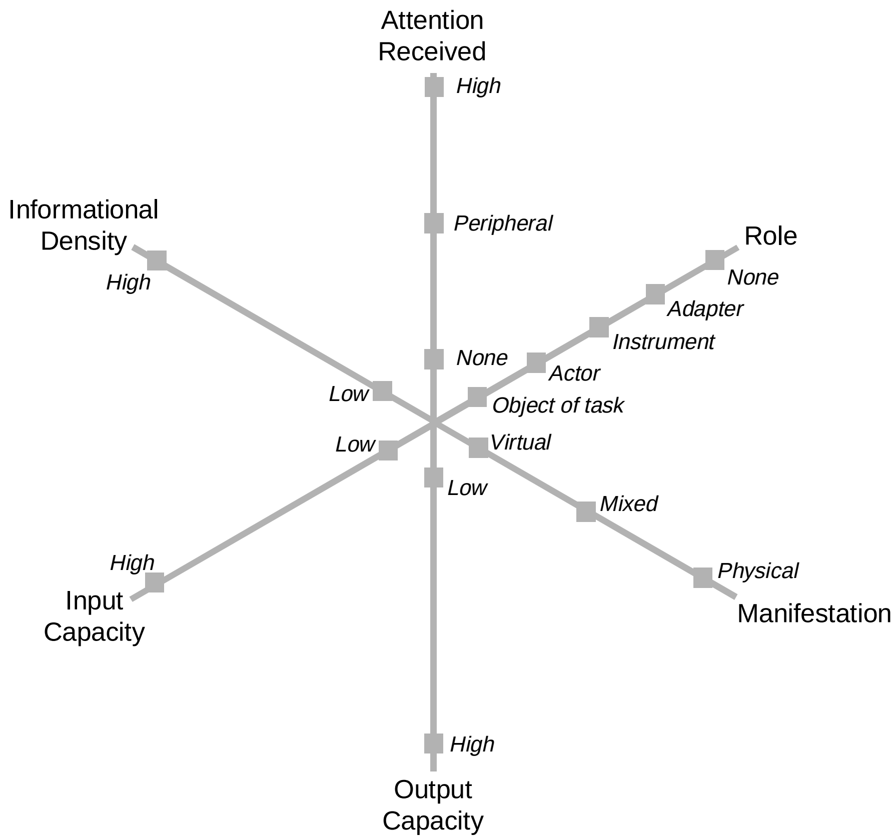

Figure 3: A Dimension Space for describing entities in the context of their physical environments. In this space, an entity is described as a plot, from the perspective of a particular actor, carrying out a particular task at some time.

As later sections show, the Dimension Space is useful as part of the system design process by helping in the design tasks listed above. Once relevant tasks and actors have been identified, the Dimension Space helps to identify how these actors carry out tasks in the context of a system mixing physical and virtual entities.

The next section introduces the Dimension Space. The following sections give examples of its application, and show how its use could form part of a design method.

4. THE DIMENSION SPACE

The Dimension Space helps designers better understand the properties of and relationships between entities. To explore these questions, designers *plot* the significant entities composing their system, both physical and virtual, in the Dimension Space. These plots are made from the point of view of a specific user of the system, carrying out a specific task at a particular time.

By constructing and viewing these plots, the system designer elaborates the implementation design space. By contrasting the properties of alternative entities on the dimensions, design issues can be exposed, and different design options can be examined. As our examples will show, the Dimension Space is not itself sufficiently rich to resolve all of these design issues. However, by exposing design issues and showing a range of design choices, the Dimension Space complements other tools that permit more detailed analysis of specific design problems.

The Dimension Space is a six-dimensional space capturing properties of the physical and virtual entities that make up an interactive system. By plotting positions on each of six axes, an entity can be described by a point in the Dimension Space. Therefore, different people may view the same entity as having different attributes, and these attributes may change over time, or as the task at hand changes.

Figure 3 shows the axes from which the Dimension Space is constructed:

- The *attention received* axis specifies how much attention the actor is currently paying to the entity. For example, if a person is writing on the Magic Board, his/her attention may be centred on the pen and whiteboard; a radio playing music may receive peripheral attention, while the desks and chairs in the room receive no attention at all.
- The *role* axis captures the purpose of the entity, from the point of view of the actor carrying out the task. For example, when erasing the content of the Magic Board, the whiteboard is the object of the task, while the brush in an instrument used in carrying out the task. Similarly, for people brainstorming using the Magic Board, the object of the task is the content of whiteboard, while the whiteboard and pens are instruments.

- The *manifestation* axis positions the entity within the physical and virtual worlds. For example, in CASPER, the needle guided by the surgeon is a purely physical entity, while the visualization showing the needle's trajectory is purely virtual. Some entities, such as the whiteboard contents of the Magic Board, may contain both physical and virtual elements.
- The *input/output capacity* axes specify the capabilities of the entity in the acquisition and rendering of information. For example, the PalmPilot® organizer is capable of presenting less visual information than a full-size colour display. A mouse may be capable of capturing finer resolution input than a vision-based finger tracker.
- The *informational density* axis expresses the relevance of the information presented by the entity. Information may be dense, implying all presented information is relevant to the task, or diffuse, implying that much of the entity's information is irrelevant, or that relevant information is hard to find.

These axes are described in detail in the following sections, followed by an example of the Dimension Space's application.

4.1 Attention Received

From the point of view of an actor carrying out a task, entities may have differing degrees of importance, and therefore be subject to varying degrees of attention. The actor's focus of attention may change as the task progresses.

Attention is a continuous axis ranging from none to high. However, we identify three points on the axis to illustrate its range of values. For example, consider the surgeon guiding a needle using the CASPER system (figure 2). The surgeon places *high* attention on the patient, on the needle being guided and on the computer-generated visualization of the needle's trajectory. The surgeon places *peripheral* attention on devices monitoring the patient's breathing and heart rate, and gives *none* of his/her attention to a waste bin in the corner of the operating room.

Attentional configuration may vary as tasks progress. For example, someone drawing on the Magic Board may initially pay no attention to the position of the projector. However, if he walks in front of the projector beam blocking projection, he may then pay peripheral attention to the projector while moving to a better location.

4.2 Role

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 describing possible roles for the entity. These roles classify the entity as: something being modified through the task, something being used to carry out the task, an actor to which part of the task has been delegated, or a connector between the virtual and physical components of the interactive system [10].

In order to better describe the different roles that entities can play in the task being carried out, consider the scenario of the CASPER system (figure 2) for helping surgeons carry out pericardial puncture operations.

- *Object of Task:* An entity is an object of the task being carried out if the task is expressed directly in terms of manipulations of this entity. Here, the task is to perform an operation on a patient, using the needle to remove effusion from the pericardial region around the patient's heart. The patient, the pericardial region and the effusion can all be seen as objects of the task.
- *Actor:* Actors are entities that may be delegated part of the task to be performed, and are capable of autonomously resolving choice points encountered in the resolution of this subtask. For example, if the surgeon finds that a light is reflecting off the computer display and interfering with his work, he might ask a nurse to move the light. The nurse is an actor, carrying out the subtask of moving the light. Actors are not restricted to being people: for example, actors may include software agents and robots.
- *Instrument:* An entity is an instrument if it is used, directly or indirectly, in the manipulation of an object of the task. Here, the needle is used to puncture the pericardium and remove effusion, so is an instrument in the task of performing the operation. Similarly, the display of the needle's position and planned trajectory are used in guiding the needle.
- *Adapter:* Some entities exist to provide an interface between the virtual world of the computer system and the physical world. Such entities are termed adapters. Here, the computer display and the localizer are adapters. An entity is an adapter if it receives its input from the physical world and provides output to the virtual world, or vice versa.
- *None:* Some entities may not contribute in any way to the task being performed and therefore have no role at the given time. For example, a waste bin in the operating theatre does not contribute to the task of guiding the needle, although it is of importance to a nurse responsible for disposing of used swabs.

4.3 Manifestation

In carrying out a task, people interact with both physical entities (such as a pen and whiteboard surface) and virtual entities (such as a spreadsheet document or a visualization of the planned trajectory of a needle.) Some entities are embodied both physically and virtually: for example, the Magic Board combines the display of physical (pen) and virtual (projected) data, while the PalmPilot organizer provides both physical and virtual buttons.

This axis provides a continuum between physical and virtual manifestation, including intermediate points of mixed physical/virtual manifestation.

Existing techniques refine this dimension, permitting further analysis of the manifestation of entities. Milgram [21] proposes that virtually manifest entities can be classified in terms of their object reality. For example, a live video image of a person is real, while a constructed avatar is virtual. Other interesting attributes include the world knowledge of the actor viewing the entity, and the representational fidelity of the entity. Both Benford and Milgram analyse the degree to which users working collaboratively can be given a sense of presence in a “shared space” [1] containing virtually constructed entities.

4.4 Input/Output Capacity

Entities differ in the degree to which they are capable of capturing or conveying information. These axes allows us to

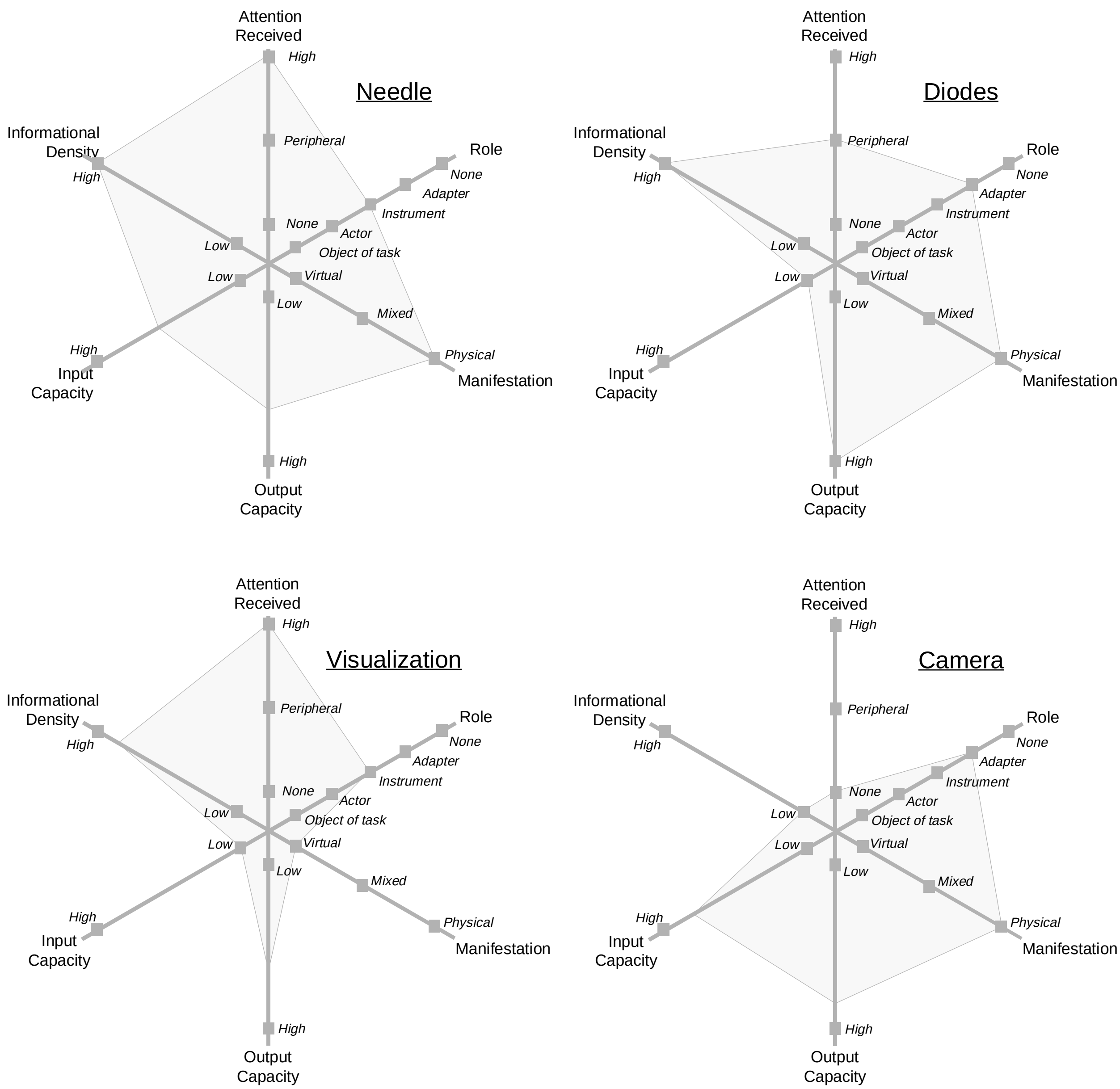

Figure 4: A set of Dimension Space plots for four entities in the CASPER application, from the point of view of a surgeon carrying out a pericardial puncture operation.

attribute input and output capacities to entities. Input capacity specifies the effectiveness of the entity at inputing data (such as the resolution or frame rate of a camera). Output capacity specifies the effectiveness of the entity in outputing data (such as display resolution.) Entities are not restricted to being solely input or output devices: for example, a haptic joystick is both an input and output device.

In the context of these axes, input is defined as information being received from other entities, while output is information provided to other entities. For example, a camera takes input from the physical scene on which it is trained, and provides output (in the form of pixel images) to software components that may process the scene.

More precisely, I/O capacity is measured as the rate at which the entity is capable of receiving/transmitting information. In information theory, capacity is formally defined in bits/second [12].

4.5 Informational Density

The input/output capacity axes described above specify the capabilities of an entity of inputing/outputing information. I/O capacity therefore allows us to discuss display devices in terms of pixels and refresh rate, microphones in terms of the range of frequencies that they are capable of capturing, or networks in terms of their bandwidth.

However, when exploring the suitability of an entity in performing some task, we are normally interested in its ability to communicate information at a much higher level. For example, in considering the effectiveness of the visualization of the needle in CASPER, we are less interested in the colour depth of the pixels on the display than in the over all effectiveness of the visualization in conveying the position of the needle with respect to the desired trajectory. *Informational density* measures the effectiveness of an entity in communicating information.

Entities providing only the information required to perform the current task at the current time have high informational density. Entities providing information that is irrelevant to the current task have lower informational density. For example, consider a teacher using a spreadsheet to find the grade of a single student. A spreadsheet containing the grades of a class of 100 students has low informational density, as the grades of the other 99 students are not relevant to the task. The organization of information provided by an entity also affects its informational density. For example, if the names in the spreadsheet are listed alphabetically, it is easier for the teacher to locate the relevant entry, therefore increasing the average relevance of information she accesses.

Informational density can be defined in terms of information theory [12]. Informally, an entity can be seen as providing information in high-level chunks [22]. For example, the CASPER visualization is ultimately made up of pixels on a CRT, which are chunked into three crosses, representing the positions of the two ends of the needle and the planned trajectory. Similarly, the information in the marks spreadsheet is chunked into names and grades. Informational density then represents the *average information content* of these chunks. This average is weighted by the likelihood of these chunks being accessed by a user performing some task. This definition has three interesting consequences:

- Unlike I/O capacity, which is absolute in value, the information density of an entity depends on the task being performed. A chunk that has little relevance to an agent performing one task may have high relevance to another agent, or may be relevant to a different task.
- Irrelevant information provided by an entity lowers its informational density. For example, in the task of finding one student's grade, a spreadsheet with 100 students has lower informational density than one with 50 students.
- Good organization of information increases informational density. For example, if users know where to find the information-rich elements of a display, they will be able to avoid irrelevant parts of the display.

5. EXAMPLES USING THE DIMENSION SPACE

This section provides a set of simple examples of the application of the Dimension Space. Following these examples, we show how the use of the Dimension Space can be placed within a design method, and suggest example design rules motivated by the Magic Board and CASPER applications.

Figure 4 shows Dimension Space plots of four entities drawn from the CASPER application (figure 2). These examples are expressed from the point of view of a surgeon who is attempting to guide a needle through a path following a pre-operative plan. We use Kiviat diagrams to plot the positions of these entities within the Dimension Space.

The first example characterizes the needle itself. The surgeon focuses high attention on the needle. As the surgeon's goal is to correctly use the needle to remove effusion from the pericardial region of the patient's heart, we characterize the needle as an instrument. The needle conveys some information to the surgeon, but not sufficient information to accurately locate it in three-space. The needle provides only information relevant to the task, and therefore has a high informational density. Finally, the needle is purely physical.

The second example plots the set of diodes (part of the localizer, attached to the needle) in the Dimension Space. The surgeon needs to be peripherally aware of the positioning of the diodes with respect to the cameras. The diodes serve as an adapter between the physical world (of the needle's position), and the virtual world of the trajectory visualization. The diodes convey sufficient information to very precisely locate the needle, and convey only that information; they therefore have both high output capacity and informational density. Diodes are purely physical.

The third example characterizes the visualization of the needle's current position in the context of the planned trajectory. The visualization receives high attention, is an instrument used in guiding the needle, carries significant information, and is purely virtual.

Finally, the Dimension Space is applied to one of the cameras used to locate the needle. Similarly to the diode, the camera receives none of the surgeon's attention, represents an adapter between the physical and virtual worlds, is purely physical, and has high input and output capacity. With respect to the task of locating the needle, the camera's output of bitmap images provides a very low informational density.

These examples have therefore shown how entities can be plotted in the Dimension Space.

6. TOWARDS METHODICAL APPLICATION OF THE DIMENSION SPACE

We now consider how the application of the Dimension Space can be integrated into the design process. Drawing from the Magic Board and CASPER systems, we present examples of specific design rules that can be applied to critique a system design at an early stage. In future work, we hope to expand this set of design rules.

Figure 5 shows a set of activities contributing to the design of a system involving physical and virtual entities. A work systems analysis process identifies the tasks that the eventual system is intended to support, as well as the actors who are to carry out the tasks. In addition, this analysis should identify any entities that are required to be part of the final system (i.e., the *fixed* entities.)

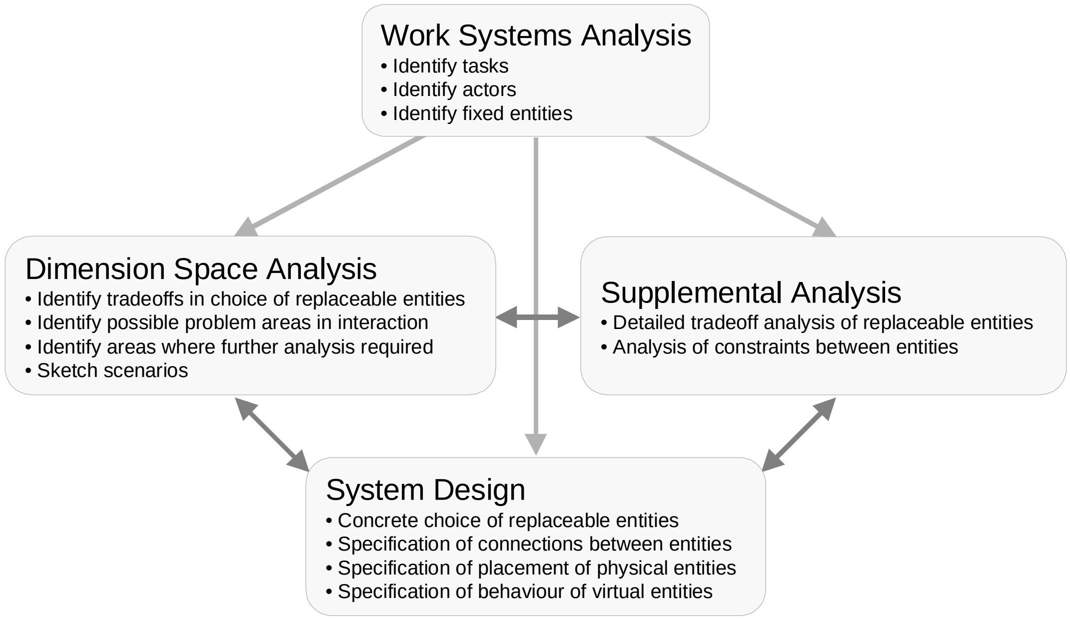

Figure 5: The Dimension Space within a system design process.

There are a number of existing methods for describing the mechanisms by which people make sense of and organize their work and then transforming these into system designs [4,23]. The Dimension Space is not intended to replace these but to build into them a capability for generating a "design space analysis" [20] tailored for hybrid physical-virtual collaborative systems. In terms of the development cycle envisioned by Beyer [3], it fits into the system design activity, between system requirements and software requirements, as part of the process of refining the entities to be reified on implementation. In terms of the later Contextual Design model, it is intended to mediate between "work redesign" and "user environment design" activities [4].

The work systems analysis leads to an eventual *system design*. This design includes specifying the physical and virtual components of the system, and how they interact. In a system design, the replaceable (or non-fixed) physical and virtual entities must be designed (or chosen). The communication patterns between these entities must be specified, including choosing the adapters that bridge the physical and virtual worlds. The physical layout of the system must be specified.

In order to arrive at such a system design, analysis must be carried out to identify appropriate tradeoffs in choices of entities making up the system, and to identify areas of the system's design that may lead to potential usability problems [19,14]. The Dimension Space helps in such analysis in identifying tradeoffs among entity choices, showing how such tradeoffs arise, and in identifying problem areas in interaction. The Dimension Space defines tradeoffs in terms of entity-information characteristics, physical and virtual, and contrasts competitors in terms of role-centrality and attentional demand. The runtime Kiviat plots are motivated by similar concerns to those behind scenario-based design [6]. They attempt to embody the relevant abstractions of artifacts and processes at work in a potential implementation.

While in some cases problems may be identified immediately from the Dimension Space itself, in other cases, the Dimension Space will suggest areas where *supplemental analysis* is appropriate. For example, when examining tradeoffs between two physical devices, cost-benefit analysis based on specification sheets may be required. As a second example, some form of model of the room may need to be constructed to support analysis of physical constraints between entities, such as observability or mechanical interference.

We anticipate that system design, Dimension Space analysis and supplemental analysis will all take place in a *coevolutionary* style [5], in which insights gained from each design activity will incrementally inform the others.

6.1 Analysis with the Dimension Space

Our ultimate goal is to be able to derive human-factors design rules for mixed physical/virtual systems, and to present heuristics for checking these rules using Dimension Space plots. While significant work is still required to meet this goal, we use three example design rules to illustrate our approach, and use the Design Space to apply these rules to parts of the CASPER and Magic Board systems. These rules are collected in figure 6.

> *Rule 1:* If at a given time, two (or more) entities in the system require high attention from an actor, then the system should be designed to permit the actor to give simultaneous attention to those entities.

Interactional discontinuity can occur when an actor is forced to divide his/her attention among two entities. An example of this is illustrated in the CASPER scenario. In this example, a surgeon guiding a needle pays high attention both to the needle

Rule 1: If at a given time, two or more entities in the system require high attention from an actor, then the system should be redesigned to permit the actor to give simultaneous attention to those entities.
Rule 2: If an actor is not aware of which parts of a mixed physical/virtual system are physical and which are virtual, then all instruments the actor applies to that entity should have the same effects on the entity's physical and virtual components.
Rule 3: If multiple actors are involved in an interaction, the system must be designed to support the coordination protocols used by these actors.

Figure 6: Example design rules that can be checked with the help of the Dimension Space.

and to the visualization of the needle's position versus the planned trajectory (figure 4). The surgeon therefore must divide his/her attention between these two entities. As discussed by Dubois *et al.* [10], the system should be re-designed to permit the surgeon to simultaneously pay attention to both the needle and visualization.

In general, if application of the Dimension Space shows that multiple entities require high attention at the same time, then the system should be designed to permit the actor in the system to simultaneously attend to the entities. Supplemental analysis is required to determine how to solve this problem. Candidate solutions could include:

- Redesigning the system so that attention to two entities is not required;
- Using different modalities for the different entities (e.g., sound and vision);
- Fusing the information presented by the entities (e.g., superimposing two displays.)

The appropriate solution will depend on the nature of the entities, and their role in the task being performed. In CASPER, solutions based on a see-through head-mounted display are being considered.

Rule 2: If an actor is not aware of which parts of a mixed physical/virtual entity are physical and which are virtual, then all instruments the actor applies to that entity should have the same effects on the entity's physical and virtual components.

A trend in the design of interactive systems has been to try to blur the distinction between physical and virtual entities. For example, the Magic Board permits people to interact with both physical and virtual representations of free-hand drawings on a whiteboard (figure 1).

Consider how a user erases content from the whiteboard. If the content is physical, he/she uses a standard whiteboard eraser brush. This brush erases physical ink, but has no effect on virtual (projected) drawings. Figure 7 tells us that the eraser brush is an *instrument* that people use to erase content from the board. Rule 2 therefore tells us that if people using the eraser cannot distinguish between the virtual and physical part of the drawing, the eraser must act in the same way on both. That is, it could be confusing or frustrating to a user of the Magic Board to not be able to predict the effect of the eraser brush. The Magic Board in fact satisfies rule 2, as the projector's output (virtual content) is clearly distinguishable from ink drawings (physical content.)

The Dimension Space helps us to identify violations of rule 2. First, we use the Dimension Space to identify what tasks involve mixed-manifestation entities as an object of a task. We then isolate which of the system's entities play the role of instruments in these tasks. At this point, supplemental analysis is required to determine whether these instruments are consistent in their effect on the virtual and physical parts of the object of the task.

When a potential violation of rule 2 has been found, there are two approaches to making the operation of the instrument more predictable:

- Redesign the operation of the instrument so that it behaves consistently over both the physical and virtual parts of the object of the task;
- Change the object of the task so that it is clear which parts are virtual and which are physical.

Rule 3: If multiple actors are involved in an interaction, the system must be designed to support the coordination protocols used by these actors.

Modern user interfaces may involve multiple actors collaborating to perform a task. For example, in the Magic Board, one or more people may write on the board at the same time. In performing the pericardial puncture procedure, a surgeon, anesthetist and nurse cooperate using CASPER. In these examples, very different styles of coordination are used. When brainstorming at the Magic Board, very informal coordination is used, where two people may write at the same time with a pen, taking turns as necessary when modifying a shared part of the drawing space. In contrast, participants in a surgical procedure have highly codified roles and procedures for coordinating their activity.

The Dimension Space allows us to identify which actors take part in a particular task, and where those actors attention rests during the task. This helps us to verify that the design does not deny actors access to the resources they require or lead to conflicts in the physical positions of people and the artifacts they share. Therefore, the Dimension Space, in identifying how people

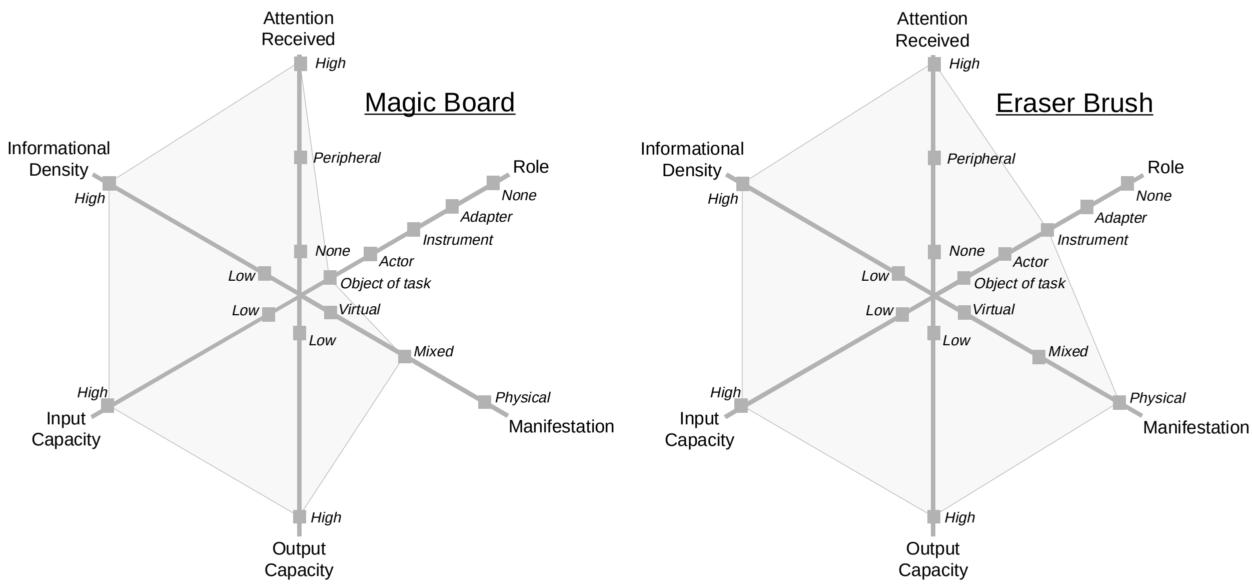

Figure 7: Two entities in the Magic Board, from the point of view of a person erasing part of the board's contents.

interact with the physical and virtual parts of the complete system, helps us to understand whether necessary coordination protocols are being supported.

For example, in the Magic Board, multiple people may draw on the board at the same time, up to the point that the space in front of the board becomes crowded. The basic task of drawing on the board is amenable to concurrent work with flexible coordination.

However, tasks involving manipulation of the virtual content of the board (copying, moving, etc.) can only be carried out by one person at a time, and to preserve camera sightlines require others to move away from the board. Therefore, for some tasks, the design of the Magic Board imposes more restrictive coordination than is desired for brainstorming activities.

Once problems in imposing inappropriately restrictive coordination have been identified, redesign of the system may be attempted in a number of ways:

- Redesign the physical layout of the system so that conflicts are avoided;
- Redesign the functionality of virtual entities so that conflict can be mediated, or to remove restrictions on coordination style;
- Rethink the coordination model (if appropriate), perhaps providing other support for coordination.

6.2 Analysis

The last section has shown how the Dimension Space can contribute to the design of interactive systems. We showed how analysis using the Dimension Space follows from a work system analysis, and complements system design. We also motivated areas where the Dimension Space serves to illustrate potential problems, showing where supplementary analysis may be required to precisely identify and resolve problems.

We further propose that the Dimension Space can be used in conjunction with design rules for systems involving multiple users and both physical and virtual artifacts. Figure 6 gave examples of three such rules. We illustrated how the Dimension Space can be used to help identify potential violations of such design rules.

This represents the early stages of work as to how the Dimension Space might fit within a method for physical/virtual interactive system design. To continue this work, we propose to:

- Investigate more deeply what forms of supplemental analysis might help in pursuing problems motivated by Dimension Space analysis.
- Following the philosophy of Cockton and Clarke [8], find systematic methods for creating links between Dimension Space plots and supplemental analyses.
- Extend the list of design rules for richly interactive systems.
- Examine the role of the Dimension Space in analyzing system breakdowns [18].

7. CONCLUSION

This paper has presented a Dimension Space for exposing design issues in the physical and virtual entities making up interactive systems. We have shown that a six-dimensional space can be used to plot entities from the point of view of an actor carrying out a task, and that these plots can expose interesting design issues for interactive systems involving multiple components and a mix of physical and virtual artifacts. Future work involves further exploration of the Dimension Space's role within a design process, and further validation through application to other systems.

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