

Designing Augmented Reality Interfaces

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Most interactive computer graphics appear on a screen separate from the real world and the user's surroundings. However this does not always have to be the case. In augmented reality (AR) interfaces, three-dimensional virtual images appear superimposed over real objects. AR applications typically use head-mounted or handheld displays to make computer graphics appear in the user's environment.

The first AR application was developed in the 1960s by Ivan Sutherland [20]. Forty years later, AR interfaces are still in their infancy. There have been a number of promising prototype applications built showing that this technology can have uses in medical, entertainment, training and the engineering fields. Great advances have been made in AR display technologies and tracking techniques, but few systems provide tools that let the user interact with and modify AR content. Furthermore, even basic interaction tasks, such as manipulation, copying, annotating and deleting virtual objects in the AR scene have been poorly addressed. Perhaps one of the greatest needs is a set of design guidelines that will enable developers to build intuitive AR applications.

At the Human Interface Technology Laboratory New Zealand (HIT Lab NZ) at the University of Canterbury, we have been developing an approach for designing intuitive AR interfaces that draws upon both virtual and physical design principles. In this article we describe our design methodology and provide several examples of how this is applied in practice.

Basic Principles

Designing an AR interface uses principles familiar in other types of interface design. The basic goal is the map user input onto computer output using an appropriate interaction metaphor. Thus there are three

elements to be considered; the physical components of the interface, the virtual visual and auditory display and the interaction metaphors used to connect these together. Figure 1 shows the close relationship between these elements.

The interface designer has available a wide variety of input and output devices and methods for mapping input to output. The challenge is to combine these together in a way that is most appropriate to the desired task, facilitates ease of use and learning and provides a high level of user performance and satisfaction. Naturally there are many valuable general interface design principles that apply to AR interfaces, such as Schneiderman's design principles for direct manipulation interfaces [18]. However there are also design principles that are more specific to augmented reality interfaces. That is the focus of our research.

When a new interface medium is developed, it typically progresses through the following stages:

1. Prototype demonstration
2. Adoption of interaction techniques from other interface metaphors
3. Development of new interface metaphors appropriate to the medium
4. Development of formal theoretical models for predicting and modeling user interactions

For example, the earliest immersive virtual reality (VR) systems were used to just view virtual scenes. Then interfaces such as 3DM [4] explored how elements of the desktop WIMP metaphor could be used to enable users to model immersively and support more complex interactions. Next, interaction techniques such as the world in miniature [19] were developed which were unique to virtual reality. Most recently, researchers are attempting to arrive at a formal taxonomy for characterizing interaction in virtual worlds that would allow developers to build 3D virtual interfaces in a systematic manner.

In many ways AR interfaces have barely moved beyond the first stage. The earliest AR

systems provided a very intuitive method for viewing three-dimensional information, but little support for creating or modifying the AR content. More recently, researchers have begun to address this deficiency. The AR modeler of Kiyokawa [9] uses a magnetic tracker to allow people to create AR content, while the Studierstube [16] project uses a pen and tablet for selecting and modifying AR objects. However these attempts have largely been based on existing 2D and 3D interface metaphors from desktop or immersive virtual environments, rather than on design principles that are unique to augmented reality.

In augmented reality there is an intimate relationship between virtual and physical objects. This suggests that one promising direction for good design may arise from taking advantage of the immediacy and familiarity of everyday physical objects for effective manipulation of virtual objects. For over a decade, researchers have been investigating computer interfaces based on real objects. We have seen the development of the digital desktop [25], ubiquitous computing [14] and tangible user interfaces (TUI) [21] among others. The goal of these efforts is to make the computer vanish into familiar objects.

Tangible user interfaces are extremely intuitive to use because physical object manipulations are mapped one-to-one to virtual object operations, and they follow a space-multiplexed input design [5]. In general, input devices can be classified as either space- or time-multiplexed. With a space-multiplexed interface, each function has a single physical device occupying its own space. In contrast in a time-multiplexed design, a single device controls different functions as different points in time. The mouse is a good example of a time-multiplexed device. Space-multiplexed devices are faster to use than time-multiplexed because users do not have to make the extra step of mapping the physical device input to one of several logical functions.

However information display with TUI can be a challenge. It is difficult to dynamically

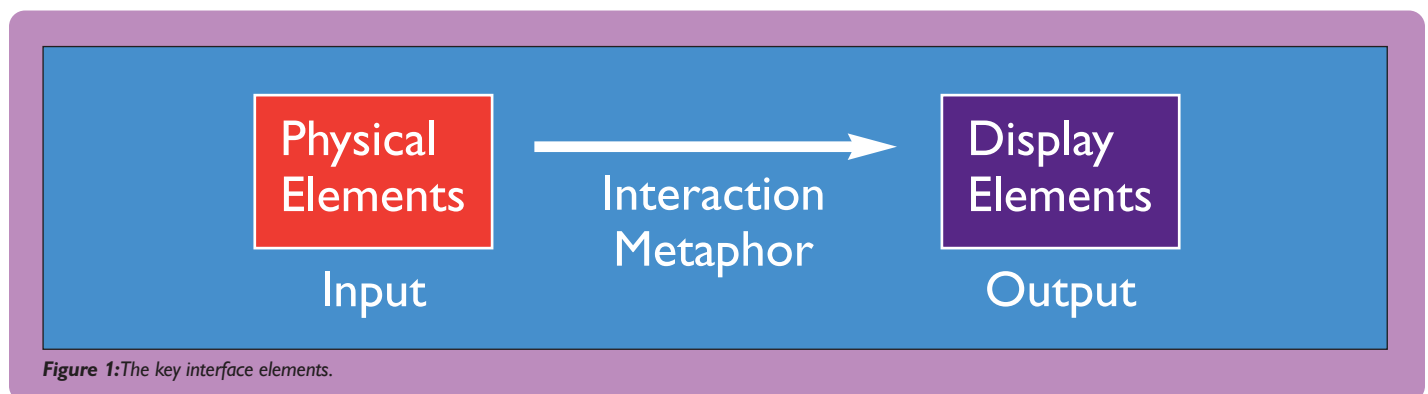


Figure 1: The key interface elements.

change an object's physical properties, so most information display is confined to image projection on objects or augmented surfaces. In those tangible interfaces that use three-dimensional graphics, there is also often a disconnect between the task space and display space. For example, in the triangles work [6], physical triangles are assembled to tell stories, but the visual representations of the stories are shown on a separate monitor distinct from the physical interface. Presentation and manipulation of 3D virtual objects on projection surfaces is difficult, particularly when trying to support multiple users each with independent viewpoints. If the information display is limited to a projection surface, users are not able to pick virtual images off the surface and manipulate them in 3D space as they would a real object.

Tangible Augmented Reality

Our approach to designing AR interfaces is one that we refer to as tangible augmented reality (tangible AR). The tangible AR approach builds on the principles suggested by TUI by coupling an AR visual display to a tangible physical interface. Thus, tangible AR interfaces are those in which 1) each virtual object is registered to a physical object and 2) the user interacts with virtual objects by manipulating the corresponding physical objects. The physical objects and interactions are equally as important as the virtual imagery and provide a very intuitive way to interact with the AR interface.

Effective tangible AR interfaces can be developed using the design principles learned from tangible user interfaces. The basic principles of TUI include:

- The use of physical controllers for manipulating virtual content.
- Support for spatial 3D interaction techniques
- Support for both time-multiplexed and space-multiplexed interaction
- Support for multi-handed interaction
- Matching the interface object affordances to the task requirements
- Supporting parallel activity where multiple objects are being manipulated
- Collaboration between multiple participants

AR interfaces that follow these design principles will provide completely seamless interaction with virtual content and so will be extremely intuitive to use. Using physical handles for virtual content enables people to use the skills they have developed throughout their lives to manipulate real objects. In addition, the use of physical objects to anchor the AR content will support natural face-to-face and remote collaboration.

When designing a tangible AR interface, the form factor and affordances of the physical objects used in the interface must be carefully considered. Ullmer describes several

approaches for selecting objects for tangible user interfaces [22]. The first is to purposely build objects using principles of industrial design and other design techniques. A second approach is to use "found" objects, objects that have been produced for another use that can be re-purposed as an interface element. For example in Hinkley's neuro-surgery planning interface, a real doll's head is used to select the viewpoint on volumetric imagery data [8]. Finally, tangible interfaces can be designed around objects that are already used in the workplace. In Mackay's AR interface for supporting aircraft controllers, she uses the physical "flight strips" that are already an integral part of the work [10]. Similarly, in McGee's RASA command and control interface, he augmented PostIt, notes that are already commonly used in command posts [12].

Using existing familiar objects may be important for getting an interface accepted by real users, however in our work we built most of the objects used. This enables us to match the affordances of the object to the requirements of the task. Norman provides some excellent guidelines for the design of objects so that their affordances are obvious [13, 14]. These include the importance of making object affordances visible, giving feedback and providing constraints. In addition he encourages the use of natural mappings and the use of a good cognitive model.

The importance of representation is introduced by Norman, and reviewed in detail by Zhang [26]. In his work he shows how the time it takes users to solve a logic puzzle is strongly dependent on the representation used and the implicit constraints they have. In a similar way, performance in a tangible AR interface is also dependent on the representations used. Those interfaces, which encapsulate interaction constraints into the form of the objects used, will be significantly easier to use.

Another important design principle is to use object representation to clearly distinguish between object functions. Ullmer proposes that the physical elements of tangible interfaces can be described in terms of "tokens" and "reference frames" [21]. Tokens are the physically manipulatable elements of tangible interfaces, while reference frames are the physical interaction spaces in which these objects are used. The object form should distinguish whether the

object is to be used as an interaction token or provide a reference frame. Objects which provide a reference frame for the interaction space are generally unmovable, while interaction objects should be easily manipulated.

The number and type of objects provide constraints on the specific AR tracking technology. One of the important requirements of tangible AR interfaces is that virtual objects should be able to appear attached to physical objects. This requires accurate tracking of the objects that serve as physical handles. As the number of objects used in the interface increases, the tracking becomes more complicated. Computer vision-based tracking is ideal for tracking several dozen objects, and provides object-centered tracking. The physical objects can be tagged with tracking markers ensuring good registration. However vision-based tracking is only useful for applications in which users can be encouraged to look at the tracking markers. Magnetic and ultrasonic tracking are alternatives that do not have this restriction but suffer from other limitations (range, number of sensors, inaccuracies). Interfaces should be designed with the limitations of the tracking system in mind.

In designing AR interfaces the display form factor must also be considered and should be matched to the nature of the task and collaboration. Current head mounted displays (HMDs) reduce peripheral awareness and so limit the user's awareness of the task space or his or her partner in a collaborative application. However a HMD does keep both hands and provide the most engaging view of the AR content. The use of an LCD display or handheld display may be also be a good choice for some applications.

Design Case Studies

In designing an AR interface, the developer must consider the physical input elements, the virtual imagery that is to be shown and the interaction metaphor that connects the two together. As we have shown in the previous section, the tangible AR approach provides a useful set of design guidelines to work from. In this section we describe some of the AR interfaces that we have developed following this approach.

Case Study 1: AR MagicLens

MagicLenses are a well-known interface technique in which semi-transparent user

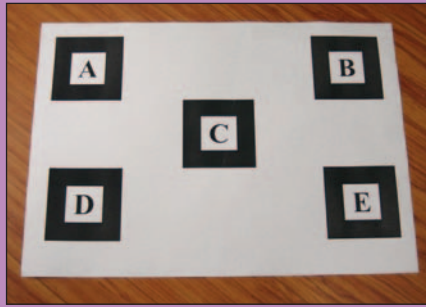
Physical Elements	Virtual Elements	Interaction Metaphor
Real handle	Magnifying glass	The user is holding a magnifying glass that is able to see inside the virtual dataset.
Paper tracking mat	Virtual Dataset	

Table 1: The AR MagicLens Interface.

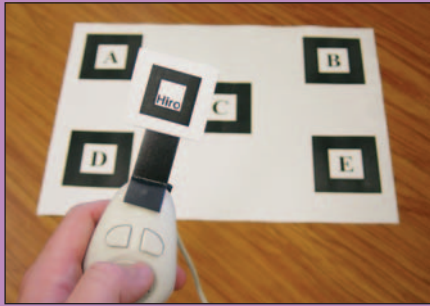
Figure 2: The MagicLens Interface Components.



a) Physical handle



b) Tracking mat



c) Real view



d) Augmented reality view

interface elements can apply transformations to whatever content lies beneath them [3]. MagicLenses can be used for magnification as well as a wealth of other effects, such as previewing image effects (blur, for example) and level-of-detail (data through the lens is rendered at a higher resolution). Several lenses can be combined to produce composite effects where they intersect. The MagicLens metaphor was extended to three dimensions by Viega et al. [23]. They implemented two types of 3D lens: a “flat” lens that projected a volume of influence into the scene, and a volumetric lens that affected content falling within a cube.

Using the design principles described above, we have developed an Augmented Reality Magic Lens implementation that enables users to intuitively view inside virtual datasets. In this case the physical elements of the interface were a real handle (a ring mouse) that the person can hold and a paper-tracking mat that serves as the coordinate space for the virtual information that is to be shown (see Figure 2a,b). When viewed in our AR application the ring mouse appeared to be a virtual magnifying glass and a virtual dataset appears over the tracking mat. The interaction metaphor is simply that the user is holding a magnifying glass that allows them to see inside the dataset being viewed. For example, when the user moves the virtual magnifying glass over the globe, the area viewed through the magnifying glass appears different (see Figure 2d).

Table 1 summarizes the various elements of the interface.

Implementation

In order to create the AR MagicLens, we use a method closely related to that of Schmalstieg and Schafler [17]. We created flat lenses by using the OpenGL stencil buffer to mask out lensed and un-lensed areas of the screen. The mask is created by rendering the lens object itself into the stencil buffer resulting in a value of 1 where the lens exists

and a value of 0 elsewhere (Figure 3a). The scene is then rendered normally in areas with values equal to 0 (Figure 3b) and with some effect applied in areas equal to 1 (Figure 3c). Finally the lens itself and its accompanying handle are drawn on top (Figure 3d). Our method supports lenses of any shape and initially we have used a circular lens mounted inside a magnifying glass model.

In our applications, tracking of the ring mouse and tracking mat was provided by the ARToolKit library [1], computer vision software that can calculate a real camera position from a set of one or more square markers. We use a video see-through AR technique in which users wear a virtual reality headset with a small video camera attached at the approximate position of their eyes. Each frame from the camera is processed by a computer which overlays the 3D graphics on the image. The image is then displayed on the user’s headset.

Applications

There are many possible applications of this lens technique for AR visualization. We created a globe visualization to demonstrate the power of this technique. In this case, a virtual globe is shown on the tracking mat. Users could then look at the globe through the lens to see a different dataset and cycle the lens through a variety of worldwide datasets while maintaining a default view outside the lens. This application presents a novel way to visualize the wealth of global information available. For example, Figure 4a

Figure 3: The process of rendering a flat lens.



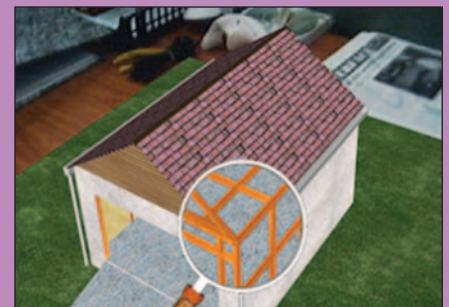
a) Stencil buffer contents. White indicates the area of the lens.



b) The area outside the lens is rendered.



c) The area within the lens is rendered with some effect. The building shell is removed, exposing the framing.

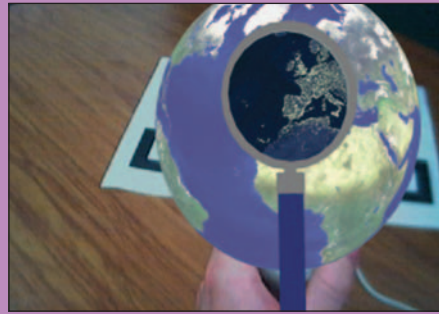


d) The magnifying glass model is rendered last.

Figure 4: Using the AR MagicLens to see different views of the earth.



a) Chlorophyll data



b) The Earth at night



c) NASA Blue Marble imagery

shows chlorophyll data, Figure 4b shows city light data and Figure 4c shows NASA's Blue Marble image. When the user has found a particularly interesting dataset, they can apply it globally so that it becomes the context rather than the focus. The main benefit of this is that the user is able to see a region of interest in a particular dataset through the virtual lens which maintaining a global context.

time. This is based on Mann's notion of Mediated Reality in which the computer can be used to filter our vision of the real world by adding virtual information [11]. Our application allows us to add virtual enhancements to real world objects (see Figure 5).

We based this application on real techniques and setups chosen by artists, painters, sculptors and designers in their everyday activ-

In addition to these real objects, we developed a simple virtual design application and a one to one mapping between the functions and behaviours of the real objects and their virtual counterparts. Thus, within this application, the user can pick up a real paintbrush, touch a virtual colour on the virtual paint palette and start painting on a real object. They can view the real world through an augmented reality headset (see Figure 6) and so they can easily see their real tools and objects at the same time as the virtual annotations being made to the objects.

Our underlying motivation for developing this application was based on the natural complementarity offered between computer graphics and real world [2]. The former offers a rapid evolving representation of objects: the latter gives a natural and intuitive environment for manipulating objects and content. For example, an architecture designer can modify a real mockup with virtual colour (and texture), adding virtual vegetations or adding a non-photorealistic rendering to it. At the same time, he also keeps the perceptual possibilities of real world and simple tangible manipulation of the mockup. In this way we combine the benefits of tangible interface manipulation with AR visual enhancements.

Our first prototype system reproduced real designer metaphors (painting, gluing and assembling). We extended later in a second application with new specific AR concepts. In

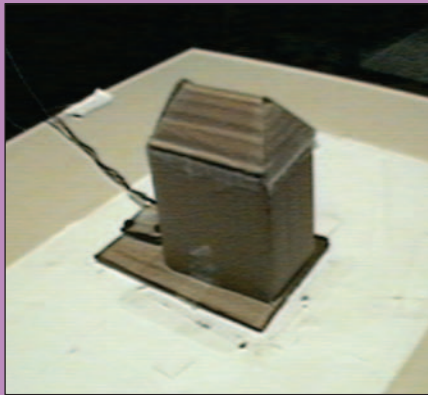


Figure 5: A "mediated" house mockup. A real model with virtual enhancements.

The tangible AR input device of the magnifying glass is universally recognized as a tool for investigation; users understand that they should peer through the lens to examine things that cannot be seen with the naked eye. With a virtual magnifying glass, we can extend this notion to allow the user to see through objects and to see the objects represented differently through the lens. Users from a variety of backgrounds have described the systems as feeling natural, both in terms of using the tangible prop as a magnifying glass and the virtual content filtering. Several users have commented on how applications like the globe demonstration would be perfect educational tools.

Case Study 2: Mixed Reality Art

In this second example, we developed an AR application to explore the possibilities of interactively "modifying reality" using computer graphics, by providing tangible AR tools for changing our vision of reality in real

ities. In a real studio, the main ingredients are a workspace, tools, materials and the medium (object). We adopt these elements in our system by providing a working surface, tracked tools, a tool palette and a scratch area for sketching and experimentation (see Figure 6).



Figure 6: The setup: the concept of the virtual studio with tangible tools (left image) and a user experimenting with the first prototype on a house mockup (right image).

this application, the user could grab a real colour from a real document (magazine, real colour palette), modify the reflectance of real objects in real time or add a virtual sketched label on a real mockup object (see Figure 7).

Implementation

The application has been developed on top of the Studierstube framework [15], a VR/AR platform that supports multiple users, devices and applications. The Studierstube rapid prototyping environment lends itself to the development of interactive editing functions, and provides the necessary handheld palette functions.

This application is currently restricted to supporting objects with known geometry, acquired off-line with established methods such as laser scanning, 3D vision reconstruction or manual digitalization. Also, while it may be interesting to work in full-scale environments, we have limited ourselves to smaller

Physical Elements	Virtual Elements	Interaction Metaphor
Real paintbrush	Brush cursor	The use is holding a real brush that is able to paint virtual graphics onto real objects.
Real props	(none)	They define 'bridge' surfaces for going from the real world content to virtual element.
Real palette	2D Hierarchical Menu	The user can select and pickup color (or tool) like he can soak a color from a palette on his brush.
Real object	A Registered Polygonal Model	Define himself as a medium (see [Underkoffler99]), the content of the application.

Table 2 summarizes the various elements of the interface.

scale models similar to those used by architects in their daily work. We concentrated on modifying those object properties that are of greatest interest in conceptual design (with a 'sketching approach'). See [7] for a more complete description of the application and its implementation.

We conducted an informal formative evaluation with professional (architectural students) and non-professional users. Users rated the provided tools as very interesting and they largely appreciated the concept. For professional users, the main use would be for interactive modification, real-time preview of designs or client presentations. The main perceived limitations were scale (as the mockup model was small), precision and efficiency. They suggested the system could be complementary to more traditional tools and 3D modeling computer tools. But we found that HMD ergonomics remains problematic and the main issue appears to be a misregistration problem. We hope that in the future optical see-through displays will support a high dynamic colour range and be comfortable enough for casual use. We are now focusing on a vision-based tracking system with a model-based approach for improved the registration.

Conclusions

In this article we have described our approach to designing augmented reality applications. By considering the form and function of the physical devices and virtual elements and the interaction metaphor used to link the two, we have been able to develop highly usable AR applications. The tangible augmented reality approach provides a natural set of design guidelines that emphasize physical object form and interactions. Using design principles adapted from tangible user interfaces, we can develop AR interfaces that support seamless interaction and are very intuitive to use. We believe that explo-

ration with tangible AR interfaces is a first step towards developing new physically based interface metaphors that are unique to augmented reality. However this approach is not ideal for all AR applications. In the future we plan to conduct more rigorous user studies to quantify the benefits of tangible AR interface, as well as developing a wider range of interaction techniques in the hope of further exploring the possible design space.

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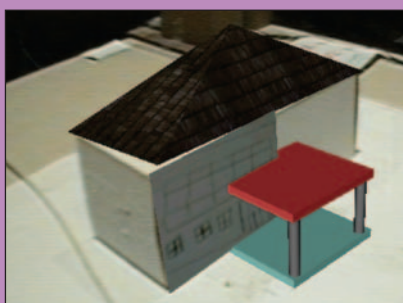
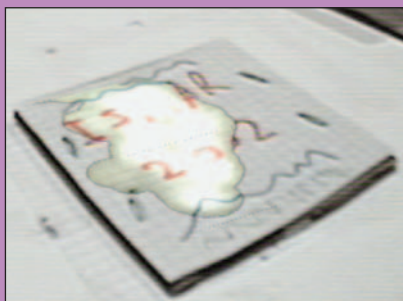


Figure 7: AR Concepts: three tools dedicated to mediated reality design. In the first one, user can grab real colour to apply virtually (top image) on a real paper. In the middle image, a user has modified appearance of a real sketching (brightness property). Finally, users can mix real sketch with virtual object to design a new house based on a cardboard box (bottom image).

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