

Recent Advances in Augmented Reality

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1. Introduction

The field of Augmented Reality (AR) has existed for just over one decade, but the growth and progress in the past few years has been remarkable. In 1997, the first author published a survey [3] (based on a 1995 SIGGRAPH course lecture) that defined the field, described many problems, and summarized the developments up to that point. Since then, the field has grown rapidly. In the late 1990's, several conferences specializing in this area were started, including the International Workshop and Symposium on Augmented Reality [29], the International Symposium on Mixed Reality [30], and the Designing Augmented Reality Environments workshop. Some well-funded interdisciplinary consortia were formed that focused on AR, notably the Mixed Reality Systems Laboratory [50] in Japan and Project ARVIKA [61] in Germany. A freely-available software toolkit (the ARToolkit) for rapidly building AR applications is now available [2]. Because of this wealth of new developments, an updated survey is needed to guide and encourage further research in this exciting area.

The goal of this new survey is to cover the recent advances in Augmented Reality that are not covered by the original survey. This survey will not attempt to reference every new paper that has appeared since the original survey; there are far too many new papers. Instead, we reference representative examples of the new advances.

What is Augmented Reality? The basic goal of an AR system is to enhance the user's perception of and interaction with the real world through supplementing the real world with 3D virtual objects that appear to coexist in the same space as the real world. Many recent papers broaden the definition of AR beyond this vision, but in the spirit of the original survey we define AR systems to share the following properties:

- 1) Blends real and virtual, in a real environment
- 2) Real-time interactive
- 3) Registered in 3D

Registration refers to the accurate alignment of real and virtual objects. Without accurate registration, the illusion that the virtual objects exist in the real environment is severely compromised. Registration is a difficult problem and a topic of continuing research.

Note that this definition of AR is not restricted to particular display technologies, such as a Head-Mounted Display (HMD). Nor is it limited to the visual sense. AR can potentially apply to all senses, including touch, hearing, etc. Certain AR applications also require removing real objects from the environment, in addition to adding virtual objects. For example, an AR visualization of a building that used to stand at a certain location would first have to remove the current building that exists there today. Some researchers call the task of removing real objects Mediated or Diminished Reality, but this survey considers it a subset of Augmented Reality.

Milgram defined a continuum of Real to Virtual environments, where Augmented Reality is one part of the general area of "Mixed Reality" (Figure 1). In both Augmented Virtuality and Virtual Environments (a.k.a. Virtual Reality), the surrounding environment is virtual, while in AR the surrounding environment is real. This survey focuses on Augmented Reality and does not cover Augmented Virtuality or Virtual Environments.

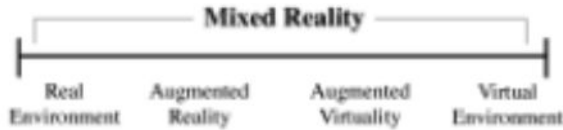


Figure 1: Milgram's Reality-Virtuality Continuum (adapted from [49])

This new survey will not duplicate the content of the 1997 survey. That paper described potential applications such as medical visualization, maintenance and repair of complex equipment, annotation and path planning. It summarized the characteristics of AR systems, such as the advantages and disadvantages of optical and video approaches to blend virtual and real, and problems in the focus and contrast of displays and the portability of AR systems. Registration was highlighted as a basic problem. The survey analyzed the sources of registration error and described strategies for reducing the errors. Please refer to the original survey for details on these topics.

The remainder of this survey organizes the new developments into the following categories: Enabling Technologies, Interfaces and Visualization, and New Applications. Enabling Technologies are advances in the basic technologies required to build a compelling AR environment: displays, tracking, registration, and calibration. The Interfaces and Visualization section describes new research in how users interact with AR systems and what they see displayed. This covers new user interface metaphors, data density and occlusion problems, more realistic rendering and human factors studies. New Applications include outdoor and mobile systems, collaborative AR, and commercial developments. This survey concludes by describing several areas requiring further research.

2. Enabling Technologies

2.1. See-Through Displays

Display technology continues to be a limiting factor in the development of AR systems. There are still no see-through displays that have sufficient brightness, resolution, field of view, and contrast to seamlessly blend a wide range of real and virtual imagery. Furthermore, many technologies that begin to approach these goals are not yet sufficiently small, lightweight, and low-cost.

Nevertheless, the past few years have seen a number of advances in see-through display technology.

Presence of well-known companies: Established electronics and optical companies, such as Sony and Olympus, now produce opaque, color, LCD-based consumer head-worn displays intended for watching videos and playing video games. While these systems have relatively low resolution (180K–240K pixels), small fields of view (ca. 30° horizontal), and do not support stereo, they are relatively lightweight (under 120 grams) and offer an inexpensive option for video see-through research. Sony introduced true SVGA resolution optical see-through displays, including stereo models (later discontinued), which have been used extensively in AR research.

Parallax-free video see-through displays: One of the challenges of video see-through display design is to ensure that the user's eyes and the cameras effectively share the same optical path, eliminating parallax errors that can affect the performance of close-range tasks [9]. The Mixed Reality Systems Laboratory developed a relatively lightweight (340 gram) VGA resolution video-see-through display, with 51° horizontal field of view, in which the imaging system and display system optical axes are aligned for each eye [84].

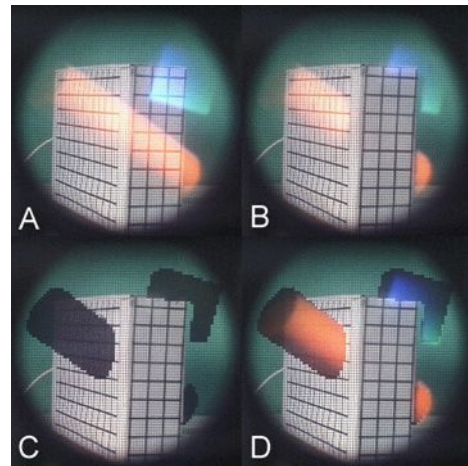


Figure 2: Images photographed through optical see-through display supporting occlusion. (a) Transparent overlay. (b) Transparent overlay rendered taking into account real world depth map. (c) LCD panel opacifies areas to be occluded. (d) Opaque overlay created by opacified pixels. (Courtesy of Kiyoshi Kiyokawa, Communications Research Laboratory.)

Support for occlusion in optical see-through displays: In conventional optical see-through displays, virtual objects cannot completely occlude real ones. Instead, they appear as "ghost" images through which real objects can be seen. One experimental display addresses this by interposing an LCD panel between the optical combiner and the real world, making it possible to opacify selected pixels [40]

(Figure 2). To avoid having the LCD appear out of focus, it is sandwiched between a pair of convex lenses and preceded by an erecting prism to invert the image of the real world.

Support for varying accommodation: Accommodation is the process of focusing the eyes on objects at a particular distance. In conventional optical see-through displays there is a conflict between the real world, viewed with correctly varying accommodation, and the virtual world, viewed on a single screen with fixed accommodation. In contrast, while conventional video see-through displays provide the same fixed accommodation distance for both real and virtual worlds, the effect is wrong except for those objects that are at the display's fixed apparent distance. Both cases can result in eyestrain and visual artifacts. Prototype video and optical see-through displays have been developed that can selectively set accommodation to correspond to vergence, by moving the display screen or a lens through which it is imaged. One version can cover a range of .25 m to infinity in .3 sec [81].

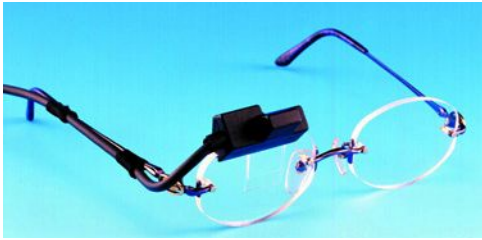


Figure 3: Minolta eyeglass display with holographic element. (Courtesy of Hiroaki Ueda, Minolta Co., Ltd.)

Eyeglass displays: Ideally, head-worn AR displays would be no larger than a pair of sunglasses. Several companies are developing displays that literally embed display optics within conventional eyeglasses. MicroOptical has produced a family of eyeglass displays in which the image of a small color display, mounted facing forward on an eyeglass temple piece, is reflected by a right angle prism embedded in a regular prescription eyeglass lens [76]. Minolta's prototype "forgettable" display is intended to be light and inconspicuous enough that the user forgets that it is being worn [37]. Others see only a transparent lens, with no indication that the display is on, and the display adds less than 6 grams to the weight of the eyeglasses (Figure 3).

Virtual retinal displays: In contrast to the virtual images produced by the displays discussed above, *virtual retinal displays* [62] form their images directly on the retina. These displays, which are being developed commercially by MicroVision, literally draw on the retina with low-power lasers whose modulated beams are scanned by microelectromechanical mirror assemblies that sweep the beam horizontally and vertically. Potential advantages include high brightness and contrast, low power consumption, and large depth of field.

2.2. Projection Displays

An alternate approach to AR is to project the desired virtual information directly on those objects in the physical world that are to be augmented. In the simplest case, the augmentations are intended to be coplanar with the surface on which they are projected and can be projected monoscopically from a room-mounted projector, with no need for special eyewear. Examples include a projection of optical paths taken through simulated elements on a virtual optical bench [86], and an application where a remote user controls a laser pointer worn by another user to point out objects of interest [47].

Generalizing on the concept of a multi-walled CAVE environment, Raskar and colleagues [63] show how large irregular surfaces can be covered by multiple overlapping projectors, using an automated calibration procedure that takes into account surface geometry and image overlap. They use stereo projection and liquid crystal shutter eyewear to visualize 3D objects. This process can also be applied to true 3D objects as the target, by surrounding them with projectors [64].

Another approach for projective AR relies on head-worn projectors, whose images are projected along the viewer's line of sight at objects in the world. The target objects are coated with a retroreflective material that reflects light back along the angle of incidence. Multiple users can see different images on the same target projected by their own head-worn systems, since the projected images cannot be seen except along the line of projection. By using relatively low output projectors, non-retroreflective real objects can obscure virtual objects.

While these are strong advantages, the use of projectors poses a challenge for the design of lightweight systems and optics. Figure 4 shows a new prototype that weighs under 700 grams [27]. One interesting application of projection systems is in Mediated Reality. Coating a haptic input device with retroreflective material and projecting a model of the scene without the device camouflages the device by making it appear semi-transparent [28] (Figure 5).



Figure 4: Experimental head-worn projective display using lightweight optics. (Courtesy of Jannick Rolland,

Univ. of Central Florida, and Frank Biocca, Michigan State Univ.)

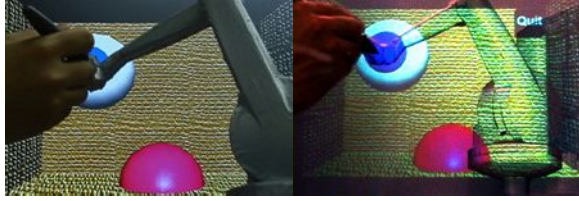


Figure 5: Projection display used to camouflage haptic input device. (left) Haptic input device normally doesn't reflect projected graphics. (right) Haptic input device coated with retroreflective material appears transparent. (Courtesy Tachi Laboratory, Univ. Tokyo)

2.3. New Tracking Sensors and Approaches

Accurately tracking the user's viewing orientation and location is crucial for AR registration. An overview of tracking systems is in [69]. For prepared, indoor environments, several systems have demonstrated excellent registration. Typically such systems employ hybrid tracking techniques (e.g., magnetic and video sensors) to exploit strengths and compensate weaknesses of individual tracking technologies. A system combining accelerometers and video tracking demonstrated accurate registration even during rapid head motion [92]. Tracking performance has also been improved through the Single Constraint at a Time (SCAAT) algorithm, which incorporates individual measurements at the exact time they occur, resulting in faster update rates, more accurate solutions, and autocalibrated parameters [90]. Two new scalable tracking systems, Constellation [19] and the HiBall [91], can cover the large indoor environments needed by some AR applications. Those trackers are available commercially from InterSense and 3rdTech, respectively.

While some recent AR systems have demonstrated robust and compelling registration in prepared, indoor environments, much remains to be done in tracking and calibration. Ongoing research includes sensing the entire environment, operating in unprepared environments, minimizing latency, and reducing calibration requirements.

Environment sensing: Effective AR requires knowledge not just of the user's location but the position of all other objects of interest in the environment. For example, a depth map of the real scene is needed to support occlusion when rendering. Real-time depth-map extraction using several cameras, where the depth map is reprojected to a new viewing location, was recently demonstrated [43]. This concept is driven to its extreme by Kanade's 3D dome with 49 cameras that capture a scene for later "virtual replay" [36].

Outdoor, unprepared environments: accurate registration today relies heavily upon modifying the environment with colored fiducial markers placed in the environment at known locations. The markers can be of various sizes to improve tracking range [13] and the computer vision techniques that track on these fiducials can update at 30 Hz [72]. But in outdoor and mobile AR applications, it is generally not practical to cover the environment with markers. A hybrid compass / gyroscope tracker demonstrated motion-stabilized orientation measurements in several outdoor locations [4] (Figure 6). With the addition of video tracking (not in real-time), the system produced nearly pixel-accurate results on known landmark features [5][93]. The TOWNWEAR system [71] uses custom packaged Fiber-Optic Gyroscopes for high accuracy and low drift rates [73]. Real-time position tracking outdoors is generally done through the Global Positioning System (GPS) or dead reckoning techniques.



Figure 6: Motion-stabilized labels annotate Phillips Tower, as seen from two different viewpoints. (Courtesy HRL Laboratories.)

Ultimately, tracking in unprepared environments may rely mostly on tracking natural features (i.e., objects that already exist in the environment, without modification) that the user sees [56]. If a database of the environment is available, tracking can be based on the visible horizon silhouette [6] or rendered predicted views of the surrounding buildings, which are then matched against the video [14]. Alternately, given a limited set of known features, it has been demonstrated that a tracking system can automatically select and measure new natural features in the environment [33]. There is a significant amount of research on recovering the camera motion given a video sequence with no tracking information. Today, those approaches do not run in real time and are best suited for special effects and post-production. However, these algorithms can potentially apply to AR if they can run in real time and operate causally (without using knowledge of what occurs in the "future"). In one such example [75], planar features, indicated by the user, are employed to track the user's change in orientation and position.

Low latency: System delays are often the largest source of registration errors. Predicting motion is one way to reduce the effects of delays; recent attempts have been made to model motion more accurately [1] and switch between multiple models [12]. System latency can be scheduled to reduce errors [31] or minimized altogether through careful system design [68]. Shifting a prerendered

image at the last instant can effectively compensate for pan-tilt motions [39]. Through image warping, such corrections can potentially compensate for delays in 6D motion (both translation and rotation) [48].

2.4. Calibration and Autocalibration

AR systems generally require extensive calibration to produce accurate registration. Measurements may include camera parameters, field of view, sensor offsets, object locations, distortions, etc. The basic principles of camera calibration are well established, and many manual AR calibration techniques have been developed. One approach to avoiding a calibration step is the development of calibration-free renderers. Since Kutulakos and Vallino introduced their approach of calibration-free AR based on a weak perspective projection model [41], Seo and Hong extended it to cover perspective projection, supporting traditional illumination techniques [74]. Another example obtained camera focal length [75] without an explicit metric calibration step. The other approach to reducing calibration requirements is autocalibration. Such algorithms use redundant sensor information to automatically measure and compensate for changing calibration parameters [23][90].

3. Interfaces and Visualization

In the last five years, AR research has become broader in scope. Besides work on the basic enabling technologies, researchers are considering problems of how users will interact and control AR applications, and how AR displays should present information.

3.1. User Interface and Interaction

Until recently, most AR interfaces were based on the desktop metaphor or used designs from Virtual Environments research. One main trend in interaction research specifically for AR systems is the use of *heterogeneous* designs and *tangible* interfaces. Heterogeneous approaches blur the boundaries between real and virtual, taking parts from both worlds. Tangible interfaces emphasize the use of real, physical objects and tools. Since in AR systems the user sees the real world and often desires to interact with real objects, it is appropriate for the AR interface to have a real component instead of remaining entirely virtual.

In one example of such an interface, the user wields a real paddle to manipulate furniture models in a prototype interior design application [38]. Through pushing, tilting, swatting and other motions, the user can select pieces of furniture, drop them into a room, push them to the desired locations, and smash them out of existence to eliminate them (Figure 7).

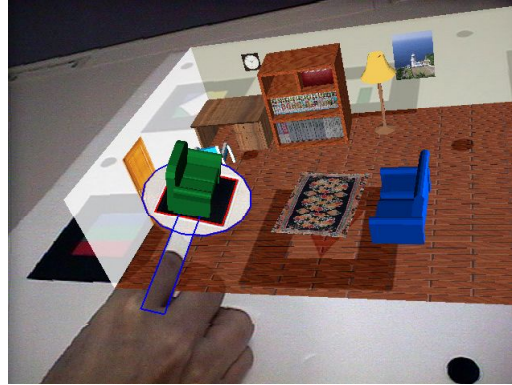


Figure 7: User wields real paddle to pick up, move, drop and destroy models. (Courtesy Hirokazu Kato)

Other examples include the Studierstube Personal Interaction Panel (PIP), several game applications, and Sony's Augmented Surfaces system. The Studierstube PIP [82] is a blank physical board that the user holds, upon which virtual controls are drawn (Figure 17). The tangible nature of the interface aids interaction with the controls. The Mixed Reality Systems Lab created several AR gaming systems. In the AR² Hockey system, two users played an "air hockey" game by moving a real object that represents the user's paddle [57]. In the RV-Border Guards game [58], users combat virtual monsters by using gestures to control their weapons and shields (Figure 8). In Sony's Augmented Surfaces system [67] (Figure 9), users manipulate data through a variety of real and virtual mechanisms. Users see data through both projective and handheld displays. A real model of a camera, placed upon the projection of a top-down view of a virtual room, generates a 3D rendering of the room from the viewpoint of that camera.



Figure 8: RV-Border Guards, an AR game. (Courtesy MR Systems Lab)



Figure 9: Heterogeneous AR systems using projected (left) and see-through handheld (right) displays. (Courtesy Jun Rekimoto, Sony Computer Science Laboratories).



Figure 10: Heterogeneous displays in EMMIE, combining head-worn, projected, and private flat-screen displays. (Courtesy A. Butz, T. Höllerer, S. Feiner, B. MacIntyre, C. Beshers, Columbia University.)

Similarly, the EMMIE system [10] mixes several display and device types and enables transferring data across devices through various operations. EMMIE supports co-located and remote collaboration amongst several simultaneous users (Figure 10). The development of collaborative AR interfaces is the other major trend in interaction research; these are discussed later in the Applications section.

Researchers have started exploring collaboration in heterogeneous environments. For example, the Studierstube and MARS [25] systems support collaboration between co-located and remote users

interacting with AR, VR and desktop displays. Another application of such cross-paradigm collaboration is the integration of mobile warfighters (engaged with virtual enemies via AR displays) collaborating with units in a VR military simulation [34][59]. Alternately, the Magic Book [22] interface allows one or more AR users to enter a VR environment depicted on the pages of the book; when they descend into the immersive VR world, the AR users see an avatar appear in the environment on the book page (Figure 17). The Magic Book requires the display to be able to completely block the user's view of the world when they descend into the VR environment.

Maximizing performance for a particular application may require tuning an interface specifically for that application [15]. The needed modifications may not be initially obvious to the designers, requiring iterative design and user feedback.

3.2. Visualization Problems

Researchers have begun to address problems in displaying information in AR displays, caused by the nature of AR technology or displays. Work has been done in visualizing the registration errors and avoiding hiding critical data due to density problems.

Error visualization: In some AR systems, registration errors are significant and unavoidable. For example, the measured location of an object in the environment may not be known accurately enough to avoid visible registration error. Under such conditions, one approach to rendering an object is to visually display the area in screen space where the object could reside, based upon expected tracking and measurement errors [44]. This guarantees that the virtual representation always contains the real counterpart. Another approach when rendering virtual objects that should be occluded by real objects is to use a probabilistic function that gradually fades out the hidden virtual object along the edges of the occluded region, making registration errors less objectionable [21].

Data density: If the real world is augmented with large amounts of virtual information, the display may become cluttered and unreadable. The distribution of data in screen space varies depending on the user's viewpoint in the real world. Julier [35] uses a filtering technique based on a model of spatial interaction to reduce the amount of information displayed to a minimum while keeping important information in view (Figure 11). The framework takes into account the goal of the user, the relevance of each object with respect to the goal and the position of the user to determine whether or not each object should be shown. The EMMIE system [10] models the environment and tracks certain real entities, using this knowledge to ensure that virtual information is not placed on top of important parts of the environment or on top of other information.



Figure 11: Data density example. Unfiltered view (left) and filtered view (right), from [35]

3.3. Advanced Rendering

Ideally, virtual augmentations would be indistinguishable from real objects. Such high quality renderings and compositions are not currently feasible in real time. However, researchers have begun studying the problems of removing real objects from the environment (a.k.a. Mediated Reality) and more photorealistic rendering (although not yet in real time).

Mediated Reality: The problem of removing real objects is more than simply extracting depth information from a scene, as discussed previously in the section on tracking; the system must also be able to segment individual objects in that environment. Lepetit discusses a semi-automatic method for identifying objects and their locations in the scene through silhouettes [42]. This enables the insertion of virtual objects and deletion of real objects without an explicit 3D reconstruction of the environment (Figure 12).



Figure 12: Virtual/real occlusions (Courtesy INRIA). The brown cow and tree are virtual; the rest is real.

Photorealistic rendering: A key requirement for improving the rendering quality of virtual objects in AR applications is the ability to automatically capture the environmental illumination information. Two examples of work in this area are an approach that uses ellipsoidal models to estimate illumination parameters [79] and Photometric Image-Based Rendering [51].

3.4. Human-Factors Studies and Perceptual Problems

Experimental results from human factors, perceptual studies and cognitive science [55] can help guide the design of effective AR systems in many areas. Drascic [16] discussed 18 different design issues that affect AR displays. The issues include implementation errors (such as miscalibration), technological problems (such as vertical mismatch in image frames of a stereo display) and fundamental limitations in the design of current HMDs (the accommodation-vergence conflict). Rolland and Fuchs performed a detailed analysis of the different human factors in connection with optical and see-through HMDs for medical applications [70]. Some significant factors include:

Latency: Delay causes more registration errors than all other sources combined [26]. More importantly, delay can reduce task performance. Delays as small as 10 milliseconds can make a statistically significant difference in the performance of a task to guide a ring over a bent wire [17].

Depth Perception: Accurate depth perception is arguably the most difficult type of registration to achieve in an AR display because many factors are involved. Some factors (such as the accommodation-vergence conflict or the fact that low resolution and dim displays make an object appear further away than it really is [16]) are being addressed through the design of new displays, as previously discussed. Other factors can be resolved through rendering occlusion correctly [70]. Eyepoint location also plays a significant role. An analysis of different eyepoint locations to use in rendering an image concluded that the eye's center of rotation yields the best position accuracy, but the center of the entrance pupil yields higher angular accuracy [87].

Adaptation: User adaptation to AR equipment can negatively impact performance. One study investigated the effects of vertically displacing cameras above the user's eyes in a video see-through HMD. Subjects were able to adapt to the displacement, but after the HMD was removed, the subjects exhibited a large overshoot in a depth-pointing task [9].

Long-Term Use: AR displays that are uncomfortable may not be suitable for long-term use. One study found that biocular displays (where the same image is shown on both eyes) caused significantly more discomfort, both in eye strain and fatigue, than monocular or stereo displays [17].

4. New Applications

In addition to advances in the application areas covered by the 1997 survey, there has been significant work that we

group into three new areas: *outdoor and mobile AR*, *collaborative AR*, and *commercial applications*. This new application work reflects a deeper understanding of the uses of AR, advances in trackers and displays, and increasingly cheap and plentiful computing power. What required a complex distributed system across a few top-of-the-line computers in 1993 can now be done with a single, off-the-shelf PC laptop; as a result, researchers can focus on more ambitious projects (such as building mobile AR systems) and new research questions (such as collaboration across multiple co-located or remote users). Advances in compute power have also enabled the first commercially-viable applications.

Before covering these new areas, we briefly highlight representative advances in the application areas covered by the 1997 survey. In [15], Curtis and his colleagues report the verification of an AR system for assembling aircraft wire bundles (this application was discussed in the original survey, but was not yet complete or tested). Although limited by tracking and display technologies, their tests on actual assembly-line workers proved that their AR system allowed workers to create wire bundles that worked as well as those built by conventional approaches.



Figure 13: 2D shop floor plans and a 3D pipe model superimposed on an industrial pipeline (Courtesy Nassir Navab, Siemens Corporate Research)

In [54], Navab and his colleagues take advantage of 2D factory floor plans and the structural properties of industrial pipelines to generate 3D models of the pipelines and register them with the user's view of the factory, obviating the need for a general purpose tracking system (Figure 13). Similarly, in [53] they take advantage of the physical constraints of a C-arm X-ray machine to automatically calibrate the cameras with the machine and register the X-ray imagery with the real objects.

Fuchs and his colleagues have continued work on medical applications of AR, refining their tracking and display techniques to support laparoscopic surgery [20]. New medical applications of AR are also being explored. For example, in [89] Weghorst describes how AR can be used to help treat akinesia (freezing gait), one of the common symptoms of Parkinson's disease.

4.1. Outdoor and Mobile

Outdoor, mobile AR systems have just begun to become feasible due to advances in tracking and computing. Mobile and outdoor AR systems enable a host of new applications in navigation, situational awareness and geo-located information retrieval.

For indoor environments, mobile AR systems of limited performance have been available for some time. NaviCam, for example, augments the video stream collected by a handheld video camera [65]. The environment was populated by a set of fiducials which served two purposes. First, the fiducials encoded the type of object that was visible. Second, because the fiducials were large (rectangular strips of known size), the augmentation could be carried out directly in "pixel space," without knowing the user's absolute position. The system provides simple information such as a list of new journals on a bookshelf. Starner et al. considered the applications and limitations of AR for wearable computers [78]. Using an approach similar to NaviCam, they developed "virtual tags" for registering graphics and considered the problems of finger tracking (as a surrogate mouse) and facial recognition.

Recent developments in low power, self-contained tracking systems (such as solid state gyroscopes and compact GPS receivers) have made it possible to measure 6D locations of users in outdoor environments. In a previous section, we discussed tracking in outdoor environments; here we focus on examples of outdoor applications.



Figure 14: Battlefield Augmented Reality System, a descendant of the Touring Machine. (Courtesy Naval Research Lab, Columbia University.)

The first outdoor system was the Touring Machine [18]. Developed at Columbia University, the system was a complete, self-contained system which included tracking (compass, GPS), 3D graphics generation on a laptop, and

a see-through HMD. The system presented the user with world-stabilized information about an urban environment (the names of academic departments on the Columbia campus). The AR display was cross-referenced with a handheld display which provided detailed information. More recent versions of this system (Figure 14) render models of buildings that used to exist on campus, display paths that users need to take to reach objectives, and play documentaries of historical events that occurred at the observed locations [24][25] (Figure 15).

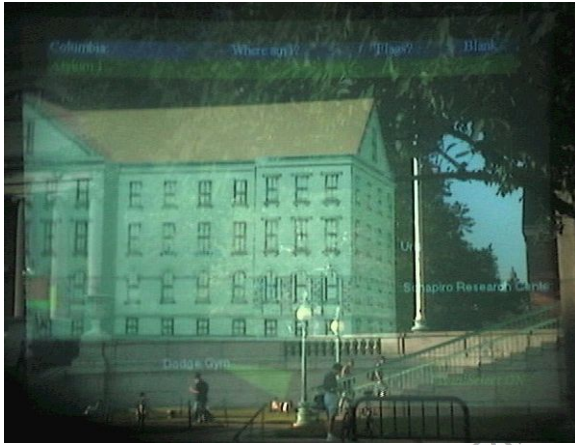


Figure 15: 3D model of demolished building is shown at its original location, viewed through see-through HMD. (Courtesy T. Höllerer, S. Feiner, J. Pavlik, Columbia University.)



Figure 16: Two views of a combined augmented and virtual environment (Courtesy Wayne Piekarsky, Bernard Gunther, and Bruce Thomas, University of South Australia).

Piekarski [59] has begun to develop user interaction paradigms and techniques for interactive model construction in a mobile AR environment. This system also enabled an outdoor user to see objects (such as an aircraft) that only exist in a virtual military simulator (Figure 16). ARQuake [85] is another example of a system that blends users in the real world with those in a purely virtual environment. A mobile AR user played a combatant in the computer game Quake, where the game ran with a virtual model of the real environment. The recently started ARCHEOGUIDE project is developing a wearable AR system for providing tourists with information about a historic site (in Olympia, Greece) [80].

Mobile AR systems must be worn, which challenges system designers to minimize weight and bulk. With current technology, one approach is to move some of the computation load to remote servers, reducing the equipment the user must wear [7][46].

The potential benefits of mobile AR have been recognized by the military community. Urban military operations (such as sniper avoidance during an embassy evacuation) inherently occur in complex, 3D environments. Future outdoor AR systems may convey crucial situational awareness information in a more intuitive manner than 2D maps.

4.2. Collaborative

An increasingly common use of computers is to support communication and collaboration. Many of the applications proposed for AR are naturally collaborative activities, such as AR assisted surgery [20] and maintenance of large pieces of equipment [54]. Other collaborative activities, especially those involving design and visualization of 3D structures, can benefit from having multiple people simultaneously view, discuss and interact with the virtual 3D models. Even collaborative activities involving 2D information can benefit from having that information spread throughout the physical world.

As Billinghurst and Kato discuss in [8], AR addresses two major issues with collaboration: *seamless* integration with existing tools and practices, and *enhancing practice* by supporting remote and co-located activities that would otherwise be impossible. Collaborative AR systems have been built using projectors, hand-held and head-worn displays. By using projectors to augment the surfaces in a collaborative environment (e.g., Rekimoto's Augmented Surfaces [67]), users are unencumbered, can see each others eyes, and are guaranteed to see the same augmentations. However, this approach is limited to adding virtual information to the projected surfaces.



Figure 17: The Studierstube (left) and Magic Book (right) collaborative AR systems, with two users wearing see-through HMDs (Courtesy Dieter Schmalstieg, Vienna University of Technology and Mark Billinghurst, Human Interface Tech. Lab.).

Tracked, see-through displays can alleviate this limitation by allowing 3D graphics to be placed anywhere in the environment. Examples of collaborative AR systems

using see-through displays include both those that use see-through handheld displays (e.g., Transvision [66]) and see-through head-worn displays (e.g., EMMIE [10], Magic Book [22] and Studierstube [83]).

When each user has his own personal display, the system can also present different information to each user, tailoring the graphics to each user's interests and skills and supporting privacy.

A significant challenge with co-located, collaborative AR systems is ensuring that the users can establish a shared understanding of the virtual space, analogous to their understanding of the physical space. The problem is that, since the graphics are overlaid independently on each user's view of the world, it is difficult to ensure that each user clearly understands what others users point at or refer to. In Studierstube, for example, the designers attempt to overcome this problem (and possible registration problems) by rendering virtual representations of the physical pointers, which are visible to all participants (Figure 17). However, this does not help when users gesture with untracked hands or refer to objects descriptively (e.g., "The lower left part of the molecule").

While numerous system designers have suggested the benefits of adaptive interfaces that are tailored to each user's interests and skills, the ability to personalize the information presented to each user also enables AR systems to present private information to individuals without fear it will be seen by others. In the EMMIE system, for example, Butz and his colleagues discuss the notion of *privacy management* in collaborative AR systems and present an approach to managing the visibility of information using the familiar metaphors of lamps and mirrors [10].

Another form of collaborative AR is found in entertainment applications. Researchers have demonstrated a number of AR games, including AR air hockey [57], collaborative combat against virtual enemies [58], and an AR-enhanced pool game [32].

4.3. Commercial Developments

Recently, AR has been used for real time augmentation of broadcast video, primarily to enhance sporting events and to insert or replace advertisements in a scene. An early example is the FoxTrax system, which highlighted the location of a hard-to-see hockey puck as it moved rapidly across the ice [11].



Figure 18: AR in sports broadcasting. The annotations on the race cars and the yellow first down line are inserted into the broadcast in real time. (Courtesy Sportvision, Inc.)

Two current examples of the use of AR in sports are shown in Figure 18 [77]. In both systems, the environments are carefully modeled ahead of time, and the cameras are calibrated and tracked. For some applications, augmentations are added solely through real-time video tracking. In the Race F/X system, the cars are also tracked with high accuracy GPS. The broadcast video is processed on-site before being broadcast, adding a few frames of latency to the video before it is transmitted. The systems work because the various parameters, such as the location of the 1st down line and chromakey color ranges for the football players, are tuned by hand in real time.

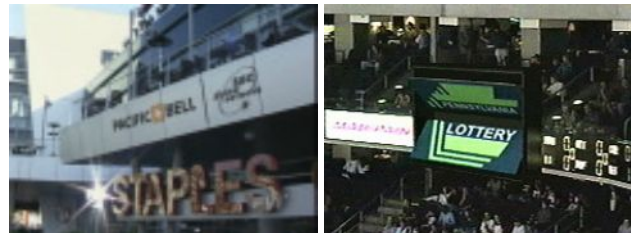


Figure 19: Virtual advertising. The Pacific Bell ad and 3D Lottery ad are AR augmentations. (Courtesy Pacific Video Image).

Virtual advertising and product insertion are increasingly common in broadcast television, as shown in Figure 19 [60]. Some examples are obvious, such as the 3D sign for the Pennsylvania Lottery. Some are less obvious, such as the Pacific Bell ad.

5. Future Work

Despite the many recent advances in AR, much remains to be done. Here are nine areas requiring further research if AR is to become commonly deployed.

Ubiquitous tracking and system portability: Several impressive AR demonstrations have generated compelling environments with nearly pixel-accurate registration. However, such demonstrations work only inside restricted, carefully prepared environments. The ultimate goal is a tracking system that supports accurate registration in any arbitrary unprepared environment, indoors or outdoors. Allowing AR systems to go

anywhere also requires portable and wearable systems that are comfortable and unobtrusive.

Ease of setup and use: Most existing AR systems require expert users (generally the system designers) to calibrate and operate them. If AR applications are to become commonplace, then the systems must be deployable and operable by non-expert users. This requires more robust systems that avoid or minimize calibration and setup requirements. Some research trends supporting this need include calibration-free and autocalibration algorithms for both sensor processing and registration.

Broader sensing capabilities: Since an AR system modifies the user's perception of the state of the real environment, ideally the system needs to know the state of everything in the environment at all times. Instead of just tracking a user's head and hands, an AR system should track everything: all other body parts and all objects and people in the environment. Systems that acquire real-time depth information of the surrounding environment, through vision-based and scanning light approaches, represent progress in this direction.

Interface and visualization paradigms: Researchers must continue developing new interface techniques to replace the WIMP standard, which is inappropriate for wearable AR systems. New visualization algorithms are needed to handle density, occlusion, and general situational awareness issues. The creation and presentation of narrative performances and structures may lead to more realistic and richer AR experiences [45].

Proven applications: Many concepts and prototypes of AR applications have been built but what is lacking is experimental validation and demonstration of quantified performance improvements in an AR application. Such evidence is required to justify the expense and effort of adopting this new technology [15].

User studies and perception issues: Few user studies have been performed with AR systems, perhaps because few experimenters have access to such systems. Basic visual conflicts and optical illusions caused by combining real and virtual require more study. Experimental results must guide and validate the interfaces and visualization approaches developed for AR systems.

Photorealistic and advanced rendering: Although many AR applications only need simple graphics such as wireframe outlines and text labels, the ultimate goal is to render the virtual objects to be indistinguishable from the real. This must be done in real time, without the manual intervention of artists or programmers. Some steps have been taken in this direction, although typically not in real time. Since removing real objects from the environment

is a critical capability, developments of such Mediated Reality approaches are needed.

AR in all senses: Researchers have focused primarily on augmenting the visual sense. Eventually, compelling AR environments may require engaging other senses as well (touch, hearing, etc.) For example, recent systems have demonstrated auditory [52] and haptic AR environments [88].

Social acceptance: Technical issues are not the only barrier to the acceptance of AR applications. Users must find the technology socially acceptable as well. The tracking required for information display can also be used for monitoring and recording. How will non-augmented users interact with AR-equipped individuals? Even fashion is an issue: will people willingly wear the equipment if they feel it detracts from their appearance?

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