Recent Advances in Augmented Reality

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In 1997, Azuma published a survey on augmented reality (AR). Here we provide a complement to that survey, denoting the rapid technological advancements since then.

What is augmented reality? An AR system supplements the real world with virtual (computer-generated) objects that appear to coexist in the same space as the real world. While many researchers broaden the definition of AR beyond this vision, we define an AR system to have the following properties:

- combines real and virtual objects in a real environment;
- runs interactively, and in real time; and
- registers (aligns) real and virtual objects with each other.

Note that we don't restrict this definition of AR to particular display technologies, such as a head-mounted display (HMD). Nor do we limit it to our sense of sight. AR can potentially apply to all senses, including hearing, touch, and smell. Certain AR applications also require removing real objects from the perceived environment, in addition to adding virtual objects. For example, an AR visualization of a building that stood at a certain location might remove the building that exists there today. Some researchers call the task of removing real objects *mediated* or *diminished reality*, but we consider it a subset of AR.

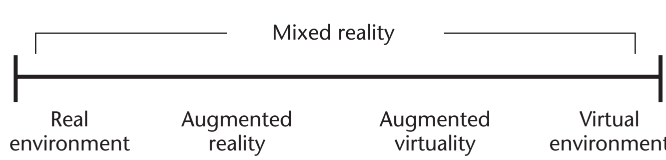
Milgram[1] defined a continuum of real-to-virtual environments, in which AR is one part of the general area of mixed reality (Figure 1). In both *augmented virtuality,* in which real objects are added to virtual ones, and *virtual environments* (or virtual reality), the surrounding environment is virtual, while in AR the surrounding environment is real. We focus on AR and don't cover augmented virtuality or virtual environments.

The beginnings of AR, as we define it, date back to Sutherland's work in the 1960s, which used a see-through HMD to present 3D graphics.[2] However, only over the past decade has there been enough work to refer to AR as a research field. In 1997, Azuma published a survey[3] that defined the field, described many problems, and summarized the developments up to that point. Since then, AR's growth and progress have been remarkable. In the late 1990s, several conferences on AR began, including the International Workshop and Symposium on Augmented Reality, the International Symposium on Mixed Reality, and the Designing Augmented Reality Environments workshop. Some well-funded organizations formed that focused on AR, notably the Mixed Reality Systems Lab in Japan and the Arvika consortium in Germany. A software toolkit (the ARToolkit) for rapidly building AR applications is now freely available at http://www.hitl.washington.edu/research/shared_space/. Because of the wealth of new developments, this field needs an updated survey to guide and encourage further research in this exciting area.

Our goal here is to complement, rather than replace, the original survey by presenting representative examples of the new advances. We refer you to the original survey[3] for descriptions of potential applications (such as medical visualization, maintenance and repair of complex equipment, annotation, and path planning); summaries of AR system characteristics (such as the advantages and disadvantages of optical and video approaches to blending virtual and real, problems in display focus and contrast, and system portability); and an introduction to the crucial problem of registration, including sources of registration error and error-reduction strategies.

Enabling technologies

One category for new developments is enabling technologies. *Enabling technologies* are advances in the basic



1 **Milgram's reality–virtuality continuum. (Adapted from Milgram and Kishino.[1])**

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technologies needed to build compelling AR environments. Examples of these technologies include displays, tracking, registration, and calibration.

2 **Concepts of optical see-through (left) and video see-through displays (right).**

Displays

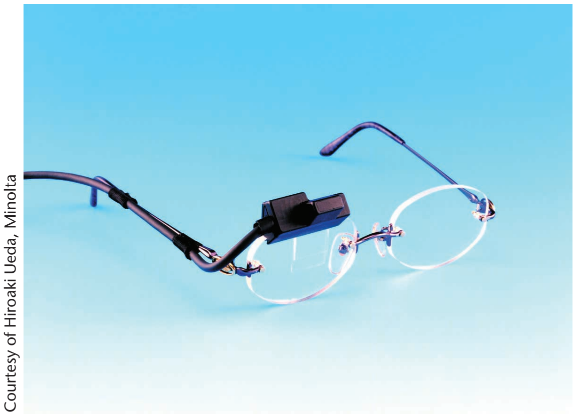
We can classify displays for viewing the merged virtual and real environments into the following categories: head worn, handheld, and projective.

Head-worn displays (HWD). Users mount this type of display on their heads, providing imagery in front of their eyes. Two types of HWDs exist: optical see-through and video see-through (Figure 2). The latter uses video capture from head-worn video cameras as a background for the AR overlay, shown on an opaque display, whereas the optical see-through method provides the AR overlay through a transparent display.

Established electronics and optical companies (for example, Sony and Olympus) have manufactured color, liquid crystal display (LCD)-based consumer head-worn displays intended for watching videos and playing video games. While these systems have relatively low resolution (180,000 to 240,000 pixels), small fields of view (approximately 30 degrees horizontal), and don't support stereo, they're relatively lightweight (under 120 grams) and offer an inexpensive option for video see-through research. Sony introduced 800 × 600 resolution, stereo, color optical see-through displays (later discontinued) that have been used extensively in AR research.

A different approach is the *virtual retinal display,*[4] which forms images directly on the retina. These displays, which MicroVision is developing commercially, 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.

Ideally, head-worn AR displays would be no larger than a pair of sunglasses. Several companies are developing displays that embed display optics within conventional eyeglasses. MicroOptical produced a family of eyeglass displays in which two right-angle prisms are embedded in a regular prescription eyeglass lens and reflect the image of a small color display, mounted facing forward on an eyeglass temple piece.[5] The intention of the Minolta prototype forgettable display is to be light and inconspicuous enough that users forget that they're wearing it.[6] 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).



Courtesy of Hiroaki Ueda, Minolta

3 **Minolta eyeglass display with holographic element.**

Handheld displays. Some AR systems use handheld, flat-panel LCD displays that use an attached camera to provide video see-through-based augmentations.[7] The handheld display acts as a window or a magnifying glass that shows the real objects with an AR overlay.

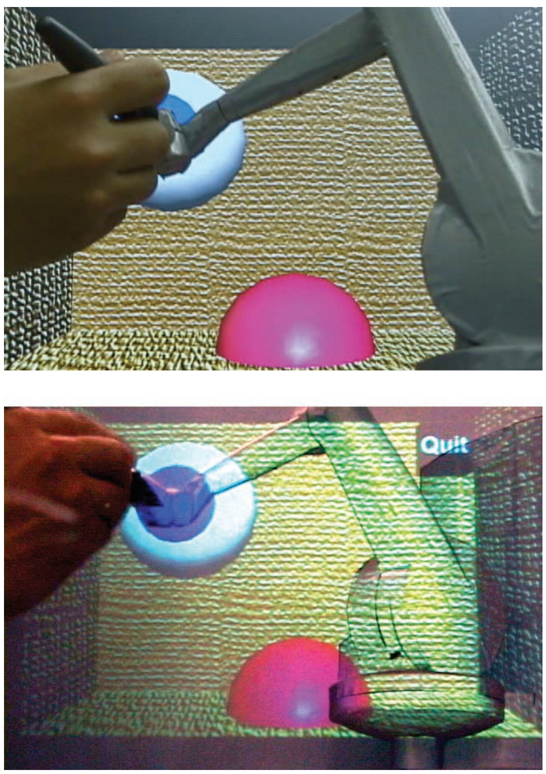
Projection displays. In this approach, the desired virtual information is projected directly on the physical objects to be augmented. In the simplest case, the intention is for the augmentations to be coplanar with the surface onto which they project and to project them from a single room-mounted projector, with no need for special eyewear. Generalizing on the concept of a multi-walled Cave automatic virtual environment (CAVE), Raskar and colleagues[8] show how multiple overlapping projectors can cover large irregular surfaces using an automated calibration procedure that takes into account surface geometry and image overlap.

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 can't be seen except along the line of projection. By using relatively low output projectors, nonretroreflective real objects can obscure virtual objects. However, projectors worn on the head can be heavy. Figure 4 (next page) shows a new, relatively lightweight prototype that weighs less than 700 grams.[9]

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 semitransparent[10] (Figure 5, next page). Other applications using projection displays include a remote laser pointer control[11] and a simulation of a virtual optical bench.[12]

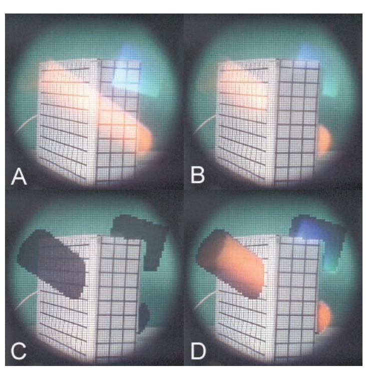
Problem areas in AR displays. See-through displays don't have sufficient brightness, resolution, field of view, and contrast to seamlessly blend a wide range of real and virtual imagery. Furthermore size, weight, and cost are still problems. However, there have been advances on specific problems. First, in conventional optical see-through displays, virtual objects can't completely occlude real ones. One experimental display addresses this by interposing an LCD panel between the optical combiner and the real world, blocking the real-world view at selected pixels[13] (Figure 6).

4 Experimental head-worn projective display using lightweight optics. (Courtesy of Jannick Rolland, University of Central Florida, and Frank Biocca, Michigan State University.)



5 Projection display used to camouflage a haptic input device. The haptic input device normally doesn't reflect projected graphics (top). The haptic input device coated with retro-reflective material appears transparent (bottom).

Courtesy Tachi Lab, University of Tokyo



6 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 Lab.)

Second, most video see-through displays have a parallax error, caused by the cameras being mounted away from the true eye location. If you see the real world through cameras mounted on top of your head, your view is significantly different from what you're normally used to, making it difficult to adapt to the display.[14] The MR Systems Lab developed a relatively lightweight (340 grams) video graphics array (VGA) resolution video see-through display, with a 51-degree horizontal field of view, in which the imaging system and display system optical axes are aligned for each eye.[15] Finally, most displays have fixed eye accommodation (focusing the eyes at a particular distance). Some prototype video and optical see-through displays can selectively set accommodation to correspond to vergence by moving the display screen or a lens through which it's imaged. One version can cover a range of .25 meters to infinity in .3 seconds.[16]

New tracking sensors and approaches

Accurately tracking the user's viewing orientation and position is crucial for AR registration. Rolland et al.[17] give a recent overview of tracking systems. For prepared, indoor environments, several systems demonstrate excellent registration. Typically such systems employ hybrid-tracking techniques (such as magnetic and video sensors) to exploit strengths and compensate weaknesses of individual tracking technologies. A system combining accelerometers and video tracking demonstrates accurate registration even during rapid head motion.[18] The Single Constraint at a Time (Scaat) algorithm also improved the tracking performance. Scaat incorporates individual measurements at the exact time they occur, resulting in faster update rates, more accurate solutions, and autocalibrated parameters.[19] Two new scalable tracking systems, InterSense's Constellation[20] and 3rdTech's HiBall,[21] can cover the large indoor environments needed by some AR applications.

Visual tracking generally relies on modifying the environment with fiducial markers placed in the environment at known locations. The markers can vary in size to improve tracking range,[22] and the computer-vision techniques that track by using fiducials can update at 30 Hz.[23]

While some recent AR systems demonstrate robust and compelling registration in prepared, indoor environments, there's still much to do 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 of the user's location and the position of all other objects of interest in the environment. For example, it needs a depth map of the real scene to support occlusion when rendering. One system demonstrates real-time depth-map extraction using several cameras, where the depth map is reprojected to a new viewing location.[24] Kanade's 3D dome drives this concept to its extreme with 49 cameras that capture a scene for later virtual replay.[25]

Outdoor, unprepared environments. In outdoor and mobile AR applications, it generally isn't practical to cover the environment with markers. A hybrid compass/gyroscope tracker provides motion-stabilized orientation measurements at several outdoor locations[26] (Figure 7). With the addition of video tracking (not in real time), the system produces nearly pixel-accurate results on known landmark features.[27,28] The Townwear system[29] uses custom packaged fiber-optic gyroscopes for high accuracy and low drift rates.[30] Either the Global Positioning System (GPS) or dead reckoning techniques usually track the real-time position outdoors, although both have significant limitations (for example, GPS requires a clear view of the sky).

Ultimately, tracking in unprepared environments may rely heavily on tracking visible natural features (such as objects that already exist in the environment, without modification).[31] If a database of the environment is available, we can base tracking on the visible horizon silhouette[32] or rendered predicted views of the surrounding buildings, which we then match against the video.[33] Alternately, given a limited set of known features, a tracking system can automatically select and measure new natural features in the environment.[34] There's a significant amount of research on recovering camera motion given a video sequence with no tracking information. Today, those approaches don't run in real time and are best suited for special effects and postproduction. 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,[35] a tracking system employs planar features, indicated by the user, 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. Researchers have attempted to model motion more accurately[36] and switch between multiple models.[37] We can schedule system latency to reduce errors[38] or minimize them altogether through careful system design.[39] Shifting a prerendered image at the last instant can effectively compensate for pan-tilt motions.[40] Through image warping, such corrections can potentially compensate for delays in 6D motion (both translation and rotation).[41]

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, and so forth. The AR community uses well-established basic principles of camera calibration and developed many manual AR calibration techniques. One way to avoid a calibration step is to develop calibration-free renderers. Since Kutulakos and Vallino introduced their approach of calibration-free AR based on a weak perspective projection model,[42] Seo and Hong have extended it to cover perspective projection, supporting traditional illumination techniques.[43] Another example obtains the camera focal length[35] without an explicit metric calibration step. The other way to reduce calibration requirements is autocalibration. Such algorithms use redundant sensor information to automatically measure and compensate for changing calibration parameters.[19,44]

Courtesy HRL Laboratories

7 **Motion-stabilized labels annotate the Phillips Tower, as seen from two different viewpoints.**

Courtesy MR Systems Lab

8 **RV-Border Guards, an AR game.**

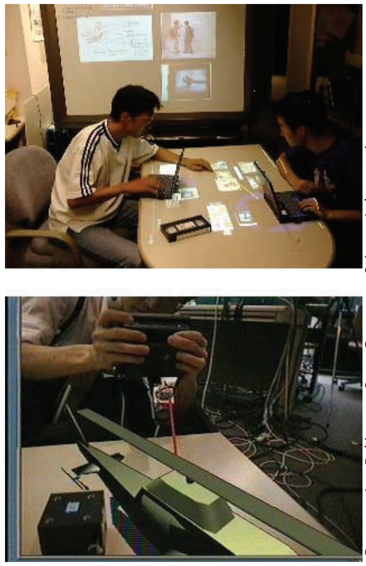
Interfaces and visualization

In the last five years, a growing number of researchers have considered how users will interact with AR applications and how to effectively present information on AR displays.

User interface and interaction

Until recently, most AR prototypes concentrated on displaying information that was registered with the world and didn't significantly concern themselves with how potential users would interact with these systems. Prototypes that supported interaction often based their interfaces on desktop metaphors (for example, they presented on-screen menus or required users to type on keyboards) or adapted designs from virtual environments research (such as using gesture recognition or tracking 6D pointers). In certain applications, such techniques are appropriate. In the RV-Border Guards game,[45] for example, users combat virtual monsters by using gestures to control their weapons and shields (Figure 8).

However, it's difficult to interact with purely virtual information. There are two main trends in AR interaction research:

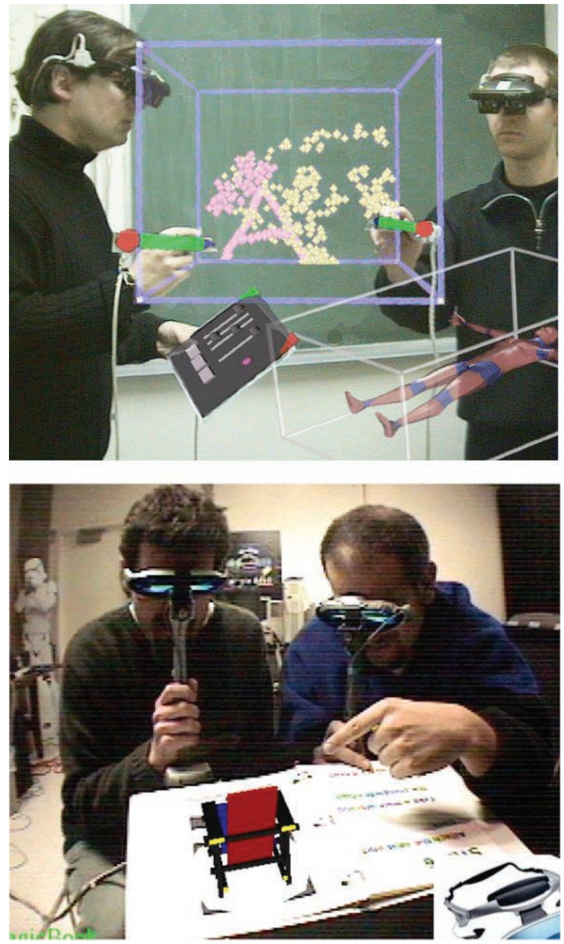


Courtesy Jun Rekimoto, Sony Computer Science Laboratories

9 **Heterogeneous AR systems using projected (top) and see-through handheld (bottom) displays.**

Courtesy A. Butz, T. Höllerer, S. Feiner, B. MacIntyre, C. Beshers, Columbia Univ.

10 **Heterogeneous displays in Emmie, combining head-worn, projected, and private flat-screen displays.**

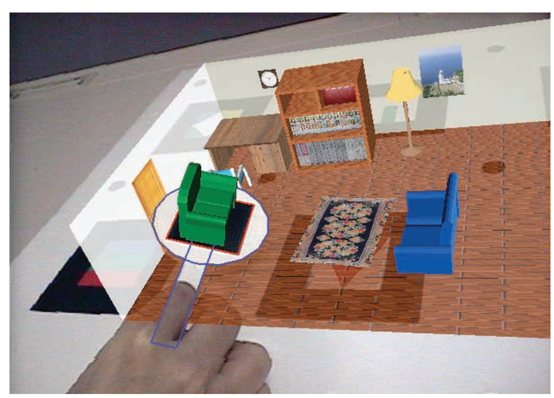


11 **The Studierstube (top) and Magic Book (bottom) collaborative AR systems, with two users wearing see-through HMDs. (Courtesy Dieter Schmalstieg, Vienna University of Technology, and Mark Billinghurst, Human Interface Technologies Lab.)**

- using heterogeneous devices to leverage the advantages of different displays and
- integrating with the physical world through tangible interfaces.

Different devices best suit different interaction techniques, so using more than one device lets an appropriate device be used for each interaction task. For example, a handheld tablet interacts well with a text document.[46] In the Augmented Surfaces system[47] (Figure 9), users manipulate data through a variety of real and virtual mechanisms and can interact with data through projective and handheld displays. Similarly, the Emmie system[48] mixes several display and device types and lets information be moved between devices to improve interaction (Figure 10). AR systems can also simulate the benefits of multiple devices. In the Studierstube system, the Personal Interaction Panel (PIP)[49] is a tracked blank physical board the user holds, upon which virtual controls or parts of the world are drawn (Figure 11). The haptic feedback from the physical panel gives similar benefits as a handheld display in this case.

Tangible interfaces support direct interaction with the physical world by emphasizing the use of real, physical objects and tools. In one example, the user wields a real paddle to manipulate furniture models in a prototype interior design application.[50] 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 remove them from the room (Figure 12). In the AR^2 Hockey system, two users



Courtesy Hirokazu Kato

12 **User wields a real paddle to pick up, move, drop, and destroy models.**

Courtesy Naval Research Lab

13 **Data filtering to reduce density problems. Unfiltered view (top) and filtered view (bottom), from Julier et al.[55]**

play an air hockey game by moving a real object that represents the user's paddle in the virtual world.[51]

Researchers have explored other interaction possibilities. For example, the Magic Book[52] depicts live VR environments on the pages of a book and lets one or more users enter one of the VR environments. When one user switches from AR into the immersive VR world depicted on the page, the other AR users see an avatar appear in the environment on the book page (Figure 11). The Magic Book takes advantage of video see-through AR displays, letting the users' views of the world be completely blocked out when they're in the VR environment.

Visualization problems

Researchers are beginning to address fundamental problems of displaying information in AR displays.

Error estimate 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 a 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 on expected tracking and measurement errors.[53] This guarantees that the virtual representation always contains the real counterpart. Another approach when rendering virtual objects that should be

Courtesy INRIA

14 **Virtual and real occlusions. The brown cow and tree are virtual; the rest is real.**

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.[54]

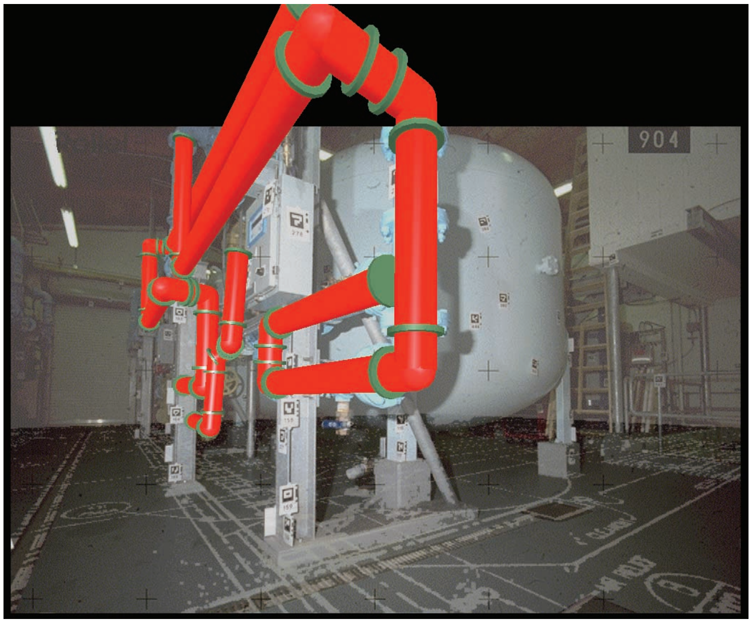
Data density. If we augment the real world with large amounts of virtual information, the display may become cluttered and unreadable. Unlike other applications that must deal with large amounts of information, AR applications must also manage the interaction between the physical world and virtual information, without changing the physical world. Julier et al.[55] use 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 13). 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 each object should be shown. In a complementary approach, Bell et al.[56] model the environment and track certain real entities, using this knowledge to ensure that virtual information isn't placed on top of important parts of the environment or other information.

Advanced rendering

For some applications, virtual augmentations should be indistinguishable from real objects. While high-quality renderings and compositions aren't currently feasible in real time, researchers are studying the problem of photorealistic rendering in AR and of removing real objects from the environment (for example, mediated reality).

Mediated reality. The problem of removing real objects goes beyond extracting depth information from a scene; the system must also segment individual objects in that environment. Lepetit discusses a semiautomatic method for identifying objects and their locations in the scene through silhouettes.[57] In some situations, this technique enables the insertion of virtual objects and deletion of real objects without an explicit 3D reconstruction of the environment (Figure 14).

Photorealistic rendering. A key requirement for improving the rendering quality of virtual objects in AR applications is the ability to automatically capture the



Courtesy Nassir Navab, Siemens Corporate Research

15 Two-dimensional shop floor plans and a 3D pipe model superimposed on an industrial pipeline.

environmental illumination and reflectance information. Three examples of work in this area are an approach that uses ellipsoidal models to estimate illumination parameters,[58] photometric image-based rendering,[59] and high dynamic range illumination capturing.[60]

Human factors studies and perceptual problems

Experimental results from human factors, perceptual studies, and cognitive science[61] can help guide the design of effective AR systems. Drascic[62] discusses 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 offer a detailed analysis of the different human factors in connection with optical and see-through HMDs for medical applications.[63] Finally, we need to better understand human factors related to the effects of long-term use of AR systems. Some significant factors include

- *Latency*. Delay causes more registration errors than all other sources combined. For close range tasks, a simple rule of thumb is that one millisecond of delay causes one millimeter of error.[64] 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.[65]
- *Depth perception*. Accurate depth perception is a difficult registration problem. Stereoscopic displays help with depth perception, but current display technologies cause additional problems (including accommodation-vergence conflicts, or low resolution and dim displays causing objects to appear further away than they really are[62]). Rendering objects with correct occlusion can ameliorate some depth perception problems.[63] Consistent registration plays a crucial role in depth perception, even to the extent that accurately determining the eyepoint location as the eye rotates can affect perception. 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.[66]
- *Adaptation*. User adaptation to AR equipment can negatively impact performance. One study investigating the effects of vertically displacing cameras above the user's eyes in a video see-through HMD showed that subjects could adapt to the displacement, but after removing the HMD, the subjects exhibited a large overshoot in a depth-pointing task.[14]
- *Fatigue and eye strain*. Uncomfortable AR displays may not be suitable for long-term use. One study found that binocular displays, where both eyes see the same image, cause significantly more discomfort, both in eyestrain and fatigue, than monocular or stereo displays.[65]

New applications

We've grouped the new applications into three areas: mobile, collaborative, and commercial applications. Before discussing these further, though, we would like to briefly highlight representative advances in the more traditional areas of assembly, inspection, and medical applications.

Curtis et al.[67] describe the verification of an AR system for assembling aircraft wire bundles. Although limited by tracking and display technologies, their tests on actual assembly-line workers prove that their AR system lets workers create wire bundles that work as well as those built by conventional approaches. This paper also emphasizes the need for iterative design and user feedback.

In their research,[68] 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 15). Similarly, 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.[69]

Fuchs and his colleagues are continuing work on medical AR applications, refining their tracking and display techniques to support laparoscopic surgery.[70] New medical AR applications are also being explored. For example, Weghorst[71] describes how to use AR to help treat akinesia (freezing gait), one of the common symptoms of Parkinson's disease.

Mobile applications

With advances in tracking and increased computing power, researchers are developing mobile AR systems. These may enable a host of new applications in navigation, situational awareness, and geolocated information retrieval.

Researchers have been investigating mobile AR research systems operating in well-prepared indoor

16 A view through a see-through HMD shows a 3D model of demolished building at its original location. (Courtesy T. Höllerer, S. Feiner, J. Pavlik, Columbia Univ.)

17 Battlefield Augmented Reality System, a descendent of the Touring Machine. (Courtesy of the Naval Research Lab.)

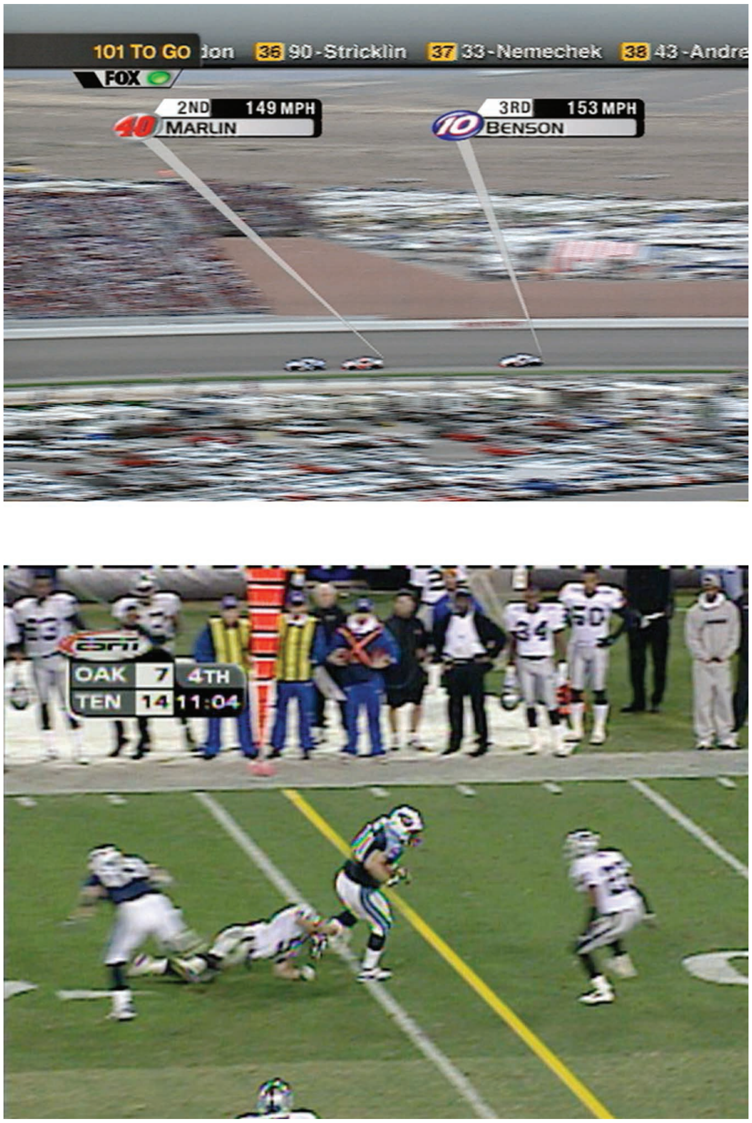
18 Two views of a combined augmented and virtual environment. (Courtesy Wayne Piekarski, Bernard Gunther, and Bruce Thomas, University of South Australia.)

environments for some time. NaviCam, for example, augments the video stream collected by a handheld video camera.[7] A set of fiducials—used to find the type of objects in view and to place the augmentation without knowing the user's absolute position—populate the environment. The system provides simple information, such as a list of new journals on a bookshelf. Starner et al. are considering the applications and limitations of AR for wearable computers.[72] Using an approach similar to NaviCam, they use virtual tags for registering graphics and consider the problems of finger tracking (as a surrogate mouse) and facial recognition.

The "New tracking sensors and approaches" section describes strategies for tracking in various outdoor environments; here we focus on examples of outdoor applications.

The first outdoor system was the Touring Machine.[46] Developed at Columbia University, this self-contained system includes tracking (a compass, inclinometer, and differential GPS), a mobile computer with a 3D graphics board, and a see-through HMD. The system presents the user with world-stabilized information about an urban environment (the names of buildings and departments on the Columbia campus). The AR display is cross-referenced with a handheld display, which provides detailed information. More recent versions of this system render models of buildings that previously existed on campus, display paths that users need to take to reach objectives, and play documentaries of historical events that occurred at the observed locations[73] (Figure 16). The Naval Research Lab (NRL) developed a similar system—the Battlefield Augmented Reality System (Figure 17)— to help during military operations in urban environments.[55] The system goal is to augment the environment with dynamic 3D information (such as goals or hazards) usually conveyed on 2D maps. Recently, the system also provides tools to author the environment with new 3D information that other system users see in turn.[74]

In the same area, Piekarski[75] is developing user interaction paradigms and techniques for interactive model construction in a mobile AR environment. This system also lets an outdoor user see objects (such as an aircraft) that only exist in a virtual military simulator (Figure 18). ARQuake,[76] designed using the same platform, blends users in the real world with those in a purely virtual environment. A mobile AR user plays as a combatant in the computer game Quake, where the game runs with a virtual model of the real environment. When GPS is unavailable, the system switches to visual tracking derived from the ARToolkit. The recently started Archeoguide project is developing a wearable AR system for providing tourists



19 **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 of NASCAR and Sportvision, top and bottom, respectively.)**

with information about a historic site in Olympia, Greece.[77] Rekimoto discusses creating content for wearable AR systems.[78]

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.[79,80]

Collaborative applications

Many AR applications can benefit from having multiple people simultaneously view, discuss, and interact with the virtual 3D models. As Billinghurst and Kato discuss,[81] AR addresses two major issues with collaboration:

- seamless integration with existing tools and practices and
- enhancing practice by supporting remote and collocated activities that would otherwise be impossible.

By using projectors to augment the surfaces in a collaborative environment (such as Rekimoto's Augmented Surfaces[47]), users are unencumbered, can see each other's eyes, and will see the same augmentations. However, this approach is limited to adding virtual information to the projected surfaces.

Tracked, see-through displays can alleviate this limitation by letting 3D graphics be placed anywhere in the environment. Examples of collaborative AR systems using see-through displays include both those that use see-through handheld displays (such as Transvision[82]) and see-through head-worn displays (such as Emmie,[48] Magic Book,[52] and Studierstube[83]). An example of multiple-system collaboration is the integration of mobile warfighters (engaged with virtual enemies via AR displays) collaborating with units in a VR military simulation.[75,84]

A significant problem with collocated, 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. Because the graphics are overlaid independently on each user's view of the world, it's difficult to ensure that each user clearly understands what other users are pointing or referring to. In Studierstube, the designers attempt to overcome this problem by rendering virtual representations of the physical pointers, which are visible to all participants (Figure 11).

Numerous system designers have suggested the benefits of adaptive interfaces tailored to each user's interests and skills. The ability to personalize the information presented to each user also lets AR systems present private information to individuals without fearing that others will see it. In the Emmie system, 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.[48]

Another form of collaborative AR is in entertainment applications. Researchers have demonstrated a number of AR games, including AR air hockey,[51] collaborative combat against virtual enemies,[45] and an AR-enhanced pool game.[85]

Commercial applications

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 highlights the location of a hard-to-see hockey puck as it moves rapidly across the ice.[86]

Figure 19 shows two current examples of AR in sports. In both systems, the environments are carefully modeled ahead of time, and the cameras are calibrated and precisely tracked. For some applications, augmentations are added solely through real-time video tracking. Delaying the video broadcast by a few video frames eliminates the registration problems caused by system latency. Furthermore, the predictable environment (uniformed players on a green, white, and brown field) lets the system use custom chroma-keying techniques to draw the yellow line only on the field rather than over the players.

With similar approaches, advertisers can embellish broadcast video with virtual ads and product placements (Figure 20).

Courtesy Pacific Video Image

20 **Virtual advertising. The Pacific Bell and Pennsylvania Lottery ads are AR augmentations.**

Future work

Apart from the few commercial examples described in the last section, the state of the art in AR today is comparable to the early years of VR—many research systems have been demonstrated but few have matured beyond lab-based prototypes.[87] We've grouped the major obstacles limiting the wider use of AR into three themes: technological limitations, user interface limitations, and social acceptance issues.

Technological limitations

Although we've seen much progress in the basic enabling technologies, they still primarily prevent the deployment of many AR applications. Displays, trackers, and AR systems in general need to become more accurate, lighter, cheaper, and less power consuming.

By describing problems from our common experiences in building outdoor AR systems, we hope to impart a sense of the many areas that still need improvement. Displays such as the Sony Glasstron are intended for indoor consumer use and aren't ideal for outdoor use. The display isn't very bright and completely washes out in bright sunlight. The image has a fixed focus to appear several feet away from the user, which is often closer than the outdoor landmarks. The equipment isn't nearly as portable as desired. Since the user must wear the PC, sensors, display, batteries, and everything else required, the end result is a cumbersome and heavy backpack.

Laptops today have only one CPU, limiting the amount of visual and hybrid tracking that we can do. Operating systems aimed at the consumer market aren't built to support real-time computing, but specialized real-time operating systems don't have the drivers to support the sensors and graphics in modern hardware.

Tracking in unprepared environments remains an enormous challenge. Outdoor demonstrations today have shown good tracking only with significant restrictions in operating range, often with sensor suites that are too bulky and expensive for practical use. Today's systems generally require extensive calibration procedures that an end user would find unacceptably complicated. Many connectors such as universal serial bus (USB) connectors aren't rugged enough for outdoor operation and are prone to breaking.

While we expect some improvements to naturally occur from other fields such as wearable computing, research in AR can reduce these difficulties through improved tracking in unprepared environments and calibration-free or autocalibration approaches to minimize set-up requirements.

User interface limitations

We need a better understanding of how to display data to a user and how the user should interact with the data. Most existing research concentrates on low-level perceptual issues, such as properly perceiving depth or how latency affects manipulation tasks. However, AR also introduces many high-level tasks, such as the need to identify what information should be provided, what's the appropriate representation for that data, and how the user should make queries and reports. For example, a user might want to walk down a street, look in a shop window, and query the inventory of that shop. To date, few have studied such issues. However, we expect significant growth in this area because research AR systems with sufficient capabilities are now more commonly available. For example, recent work suggests that the creation and presentation of narrative performances and structures may lead to more realistic and richer AR experiences.[88]

Social acceptance

The final challenge is social acceptance. Given a system with ideal hardware and an intuitive interface, how can AR become an accepted part of a user's everyday life, just like a mobile phone or a personal digital assistant (PDA)? Through films and television, many people are familiar with images of simulated AR. However, persuading a user to wear a system means addressing a number of issues. These range from fashion (will users wear a system if they feel it detracts from their appearance?) to privacy concerns (we can also use the tracking required for displaying information for monitoring and recording). To date, little attention has been placed on these fundamental issues. However, these must be addressed before AR becomes widely accepted. ■

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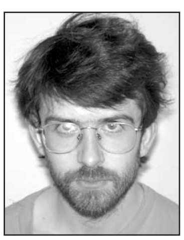

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