Mixed Reality: Future Dreams Seen at the Border between Real and Virtual Worlds

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We describe some of the technical achievements we made in the Mixed Reality (MR) Project in Japan.

Mixed reality (MR) is a kind of virtual reality (VR) but a broader concept than augmented reality (AR), which augments the real world with synthetic electronic data. On the opposite side, there is a term, augmented virtuality (AV), which enhances or augments the virtual environment (VE) with data from the real world. Mixed reality covers a continuum from AR to AV. This concept embraces the definition of MR stated by Paul Milgram.[1]

We participated in the Key Technology Research Project on Mixed Reality Systems (MR Project) in Japan. The Japanese government and Canon funded the Mixed Reality Systems Laboratory (MR Lab) and launched it in January 1997. We completed this national project in March 2001.

At the end of the MR Project, an event called MiRai-01 (mirai means *future* in Japanese) was held at Yokohama, Japan, to demonstrate this emerging technology all over the world. This event was held in conjunction with two international conferences, IEEE Virtual Reality 2001 and the Second International Symposium on Mixed Reality (ISMR) and aggregated about 3,000 visitors for two days.

Aim of the MR project

This project aimed to produce an innovative information technology that could be used in the first decade of the 21st century while expanding the limitations of traditional VR technology. The basic policy we maintained throughout this project was to emphasize a pragmatic system development rather than a theory and to make such a system always available to people. Since MR is an advanced form of VR, the MR system inherits a VR characteristic—users can experience the world of MR interactively. According to this policy, we tried to make the system work in real time. Then, we enhanced each of our systems in their response speed and image quality in real time to increase user satisfaction. We describe the aim and research themes of the MR Project in Tamura et al.[2]

To develop MR systems along this policy, we studied the fundamental problems of AR and AV and developed several methods to solve them in addition to system development issues. For example, we created a new image-based rendering method for AV systems, hybrid registration methods, and new types of see-through head-mounted displays (ST-HMDs) for AR systems. Three universities in Japan—University of Tokyo (Michitaka Hirose), University of Tsukuba (Yuichic Ohta), and Hokkaido University (Tohru Ifukube)—collaborated with us to study the broad research area of MR. The sidebar, "Four Types of MR Visual Simulation," and Tamura's article[3] describe how our MR technology creates the continuum proposed by Milgram by merging the real and virtual worlds in various ways.

Achievements

The MR Project[4] led to many specific research projects, yielding several significant achievements in multiple areas. Here we highlight some of the technical achievements we made in this challenging area.

Achievements in the AV field

For AV systems, the project focused on a new paradigm called image-based rendering (IBR).

Image-based rendering in VR space. Our IBR method based on ray space data, like other IBR methods, could reconstruct an arbitrary view directly from captured multiple images. CyberMirage is a system that uses the method and integrates it with a conventional polygon-based graphic system. We designed the system for cybershopping in a virtual mall with photorealistic products.[5]

Visualization of large spaces. AV methods weren't only used to render complex objects, but also to construct a large-scale VE such as an existing city. The

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Four Types of MR Visual Simulation

To show the continuity between augmented virtuality (AV) and augmented reality (AR), we exhibited four types of MR systems on the same theme at MiRai-01.[1] All of them were visual simulations that put some virtual buildings onto the outside scene of the real world.

The first system, called Cybercity Walker 2001, is a typical AV system. The system reconstructs an observer's path as he or she walks through the system's virtual world from the database of video images systematically captured by driving a car with seven video cameras and various sensors on its roof. The reconstructed scene is projected onto a wide screen surrounding an observer and he or she can run while looking around and select where to go (Figure A). Since the moving speed is controllable, observers can experience the system as a walker or as a car racer. This system can superimpose virtual buildings onto a sequence of reconstructed scenes. It's a unique system that people want to use for city planning or tour guides. We also expect that it will be used to archive scenery of cultural value.

The second system, Wisteria World 2001, incorporates MR functions into a telepresence system so a user can control the image-capturing device at a remote site. Our prototype system uses a miniature model of a town with a motion-control camera in it. The model is 1/87 scale and has enough precision that it looks like a real town when seen through the video camera (Figure B1). Users can walk through the remote town and make a visual simulation by putting virtual buildings in it using a joystick control. They can also fly over the town as if they're helicopter pilots or look around the town from inside a virtual building. Multiple light sources can be turned on and off by remote control so that users can attain photometric consistency between live images and computer-generated images (Figure B2). At MiRai-01, we demonstrated this system while placing the model in our lab and connecting the lab and exhibition hall with a wide-area network using an optical beam.

The third system, Seeing Through, Inside Out, was actually a byproduct of the fourth system, which is a mobile system. By wearing a see-through HMD, users can see the MR even though they see it through windows

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A Cybercity Walker 2001. Walking through and looking around a realistic cyberspace reconstructed from the physical world.

B Wisteria World 2001. (1) The model town is at 1/87 scale. (2) Telepresence over a broadband network.

aim of Cybercity Walker was to enable complete virtualization of an actual city space.[6] Users of this system can walk through and look around a cyber city space with high photoreality, although the space was modeled without any geometric data. Unlike the Aspen Movie Map,[7] the space can be augmented with virtual buildings.

PC-based rendering systems. These systems were originally based on the SGI Onyx2 systems and were downsized to PCs. At the same time, we tried to enhance image quality with improved image-capturing devices and to compress the data so that it can be handled on a PC. For the real-time rendering of ray space data, we developed dedicated hardware as an acceleration board for a PC.[8]

Achievements in the AR field

As the counterpart of AV, an AR system superimposes computer-generated images and data onto the real scene. We developed 12 AR systems throughout the MR Project and the experience gave us important knowledge about various types of devices and methods that make an AR system robust.

Robust registration scheme. The biggest problem for an AR system is the geometric registration of virtual space onto the real space.[9] After much trial and

C **Seeing Through, Inside Out. (1) Real landscape through a window. (2) Augmented view with computer-generated buildings and characters.**

D **(1) Wearing a helmet and a backpack in a real outdoor environment. (2) Augmented view (virtual building and tree are added in the center).**

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inside a room. At MiRai-01, we exhibited a landscape simulation, but an entertainment system in which users can fight with virtual characters generated by the system was far more pleasing to the participants (Figure C). The defining characteristic of the system—enjoying outdoor MR effects indoors—probably will be used in various theme parks and other entertainment sites.

The last system, Towards Outdoor Wearable Navigator with Enhanced and Augmented Reality (TOWNWEAR), is a purely mobile outdoor system consisting of a helmet with an ST-HMD, an optical fiber gyro, and a backpack with a portable PC and battery. The total weight of the system is 7.2 kg. It isn't light enough as a practical mobile system, since we focused on its performance rather than its weight. The system uses a technique of vision-assisted registration to adjust the drift of the optical fiber gyro and presently performs with one of the best spatial registration accuracies in the world. The system demonstrated at MiRai-01 had a function to install virtual statues in the open space in addition to the functions for landscape simulation and town navigation (Figure D). Although many landscape simulation systems exist, few of them can actually place a correct-sized virtual object into the real world. This system can.

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1. H. Tamura, "Overview and Final Results of the MR Project," *Proc. 2nd Int'l Symp. Mixed Reality* (ISMR 2001), Virtual Reality Soc. Japan, Tokyo, 2001, pp. 97-104.

error, we found that the hybrid method that adjusts the output of commercially available physical head trackers with the vision-based method showed good and reliable performance.[10]

Innovative see-through HMD. In addition to the registration problem, the see-through functionality is the critical part of any AR system. Therefore, we developed our own ST-HMDs for various applications that

See-through HMDs for Mixed Reality

In the MR Project, we developed our own innovative see-through head-mounted displays (ST-HMDs) and applied them to the actual system. Some of them are optical ST-HMDs and the others are video ST-HMDs. All of our HMDs use a pair of free-form-surface prisms based on the theory of off-axial optics.[1]

The video ST-HMD is an opaque HMD with one or two cameras. The see-through function, overlaying computer-generated images on the video captured by the camera, isn't done in the HMD, but in a separate computer or a special device. The simplest way to develop such an HMD is to place one or two video cameras on an opaque HMD. The simple structure captures images as though eyes of an observer are placed at the upper front position of the actual eye and prevents observers from looking at 3D objects nearer to them correctly. To solve this problem, we designed a new type of video ST-HMD with a pair of built-in video cameras so that the optical axes of camera and display optics coincide (Figure E).[2] We named this stereoscopic parallax-free HMD—which has 929,000 pixels, VGA resolution, and a viewing angle of 51 degrees for each eye—Co-Optical Axis See-through Augmented Reality (COASTAR) and used it for all the video see-through AR applications in the project.

The next challenge was to develop an ST-HMD for outdoor use. Optical ST-HMDs can present more realistic scenes to an observer than video ST-HMDs can. They're also safer, even when the power is off. On the other hand, the optical ST-HMD isn't suitable for light. Thus, we need to incorporate a function to adjust the amount of light coming into the HMD from the real scene. In addition, it's convenient to have a video camera for vision-based registration. From the viewpoint of HMD design, we decided to place a camera at the center of an observer's eyes and adopt an optical system that places a liquid crystal display (LCD) panel near the tail of each eye. We also developed a bright backlit panel using white light-emitting diodes (LEDs). The result is an optical ST-HMD of 1,558,000 pixels, SVGA resolution, and a viewing angle of 33 degrees (Figure F). This type of HMD mounts on a helmet in the TOWNWEAR system.

Our final challenge was to develop an HMD having video and optical see-through functions. Such an HMD should have a pair of built-in video cameras placed as in COASTAR. The optical axis of the third optics, optical see-through optics, should also coincide with the axes of the other optics to realize a parallax-free HMD. This type of HMD provides an advantage of using the optical ST method while capturing a scene without any parallax into stereoscopic video for the vision-based registration. As shown in Figure G, the HMD has a pair of half-mirrors between the LCD panels and video camera. In this structure, the cameras capture images of the outside mixed with images shown on the LCDs. Therefore, the cameras and LCDs are controlled so that the shutters of cameras close while the LCDs are working and open to capture the outside images while the LCDs aren't showing anything.

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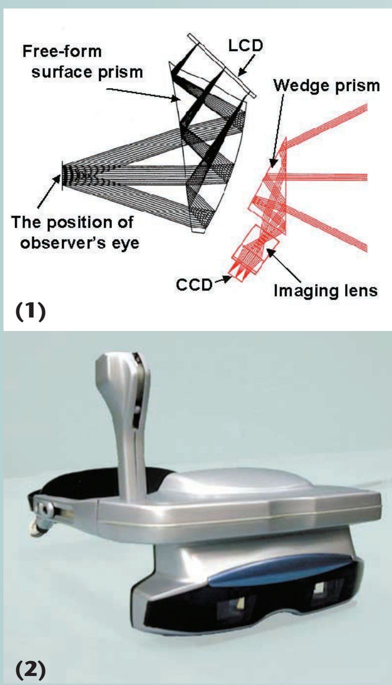
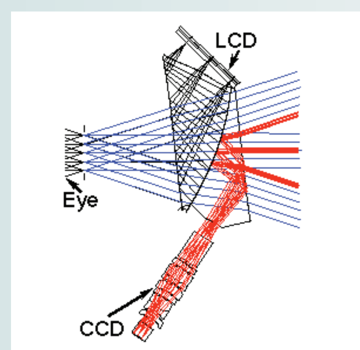


E COASTAR—parallax-free video ST-HMD. (1) Diagram of product. (2) Actual product.

F Optical see-through HMD for outdoor use.



G Optical and video see-through unit.

could support the optical and video see-through methods. See the sidebar "See-through HMDs for Mixed Reality" for more details.

Novel depth-keying method. Another challenge was to solve the difficult problem of occlusion between real and virtual objects. We ordered a special device that could measure the depth of the real world from images acquired by five video cameras using the multi-baseline stereo method. With the depth data, the depth-

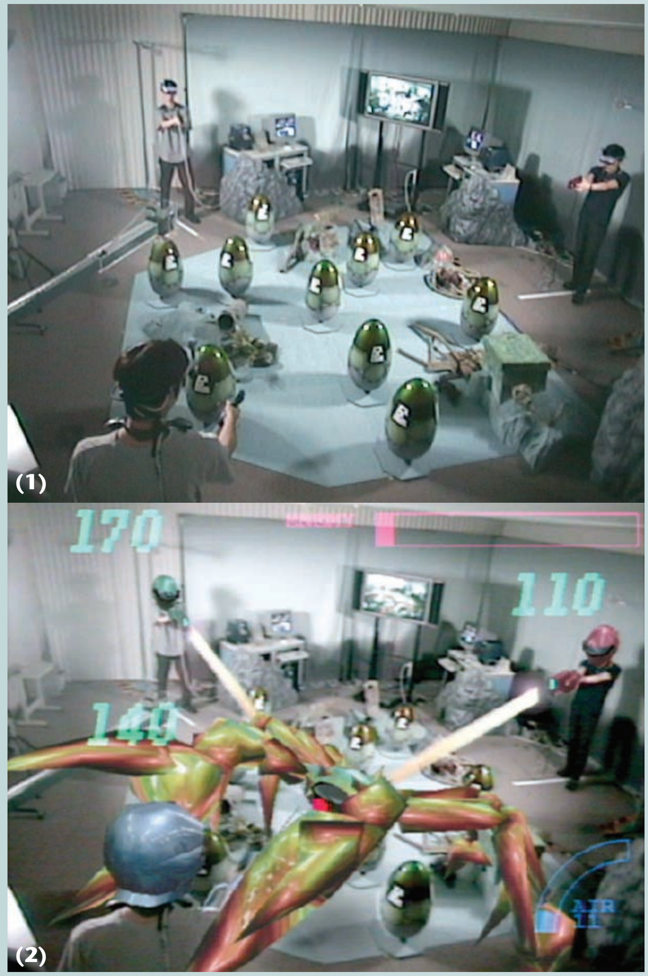
MR Attractions

Here we introduce three MR systems developed through the MR Project for MiRai-01.

AquaGauntlet

This is a multiplayer entertainment game in MR space developed as an example of a collaborative AR (for more information on AquaGauntlet, see http://www.mr-system.co.jp/project/aquagauntlet/index.html). Players wearing video ST-HMDs shoot computer-generated creatures superimposed onto a real scene to gain a score. Note that the creatures move around the 3D MR space (Figure H). Since the guns of this system are incorporated with vibrating motors, players can feel mechanical shock when they shoot invaders. The three major visual effects implemented in this system are shades cast onto a real world by virtual creatures, environmental mapping onto the creatures, and occlusions between real and virtual objects.

In conventional video gaming, players destroy enemies or race against opponents within the limited screen of a boxy monitor. In MR entertainment such as AquaGaunlet, players can use all the wide space that meets their eyes. Since we can freely design both the real and virtual worlds, we can build up contents that suit not only players but also galleries.



H AquaGauntlet—a multiplayer entertainment game in MR space. (1) Without augmentation and (2) with see-through augmentation.

2001: An MR Space Odyssey

This is an application of MR technology to visual effects (VFX) for filmmaking, especially to show the power of real-time depth-keying technology. A sequence of VFX in a feature film—such as a composite of live action scenes with computer-generated images—is usually made in the postproduction process. On the other hand, our MR technology that merges the real and virtual worlds achieves real-time interaction between users and the MR space. In this sense, MR is a real-time VFX seen from an observer's viewpoint.

We can apply this advantage to filmmaking in the following ways:

- A director and a cinematographer can see actions in a studio and the results of composition in real time. They can use the depth data taken at the same time for highly precise post-production.
- Actors can rehearse while seeing virtual characters by wearing ST-HMDs.

We built these systems by using the highest level of MR technologies accumulated throughout the MR Project and demonstrated them at MiRai-01.[1] Figure I shows how the director or audience can experience the scene of an actress fighting with an alien in real time. Since the actress is wearing a video ST-HMD, audiences can also enjoy scenes from her viewpoint.

Clear and Present Car

The MR technology that can place virtual objects onto the physical space at the scale of 1:1 without any positional misalignment have ample possibilities of application for the industrial and business fields. Among them, automobile visualization is an attractive application of this technology.

ART+COM AG in Germany has already developed an excellent VR system named Virtual Car for automobile marketing. We enhanced this system with our MR technology.[2] We call our system Clear and Present Car. Customers can see stereoscopic views inside and outside a Mercedes Benz S Class or A Class by wearing a video see-through HMD. Customers can also change the vehicle's basic characteristics—such as paint color, wheel rims, or upholstery—by using an interactive device with push buttons. By sitting on a physical driver's seat, customers can check the interior of a car and how it matches to the outside scene while feeling the real seat (Figure J). This system will help in designing and promoting cars.

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I 2001: An MR Space Odyssey. We showed the audience MR composite images in real time as an attraction.

J Clear and Present Car. It's more effective when you experience it on the real seat.

keying method lets us render complicated occlusion effects between both worlds. This range finder is now the key component for high-level MR systems that perform real-time depth keying.

Outdoor wearable system. We redesigned the AR systems that were limited to indoor use into the system for outdoor use in a wearable fashion. Unlike most wearable systems, the essence of AR—that is, real-time interaction and precise registration between real and virtual worlds—is maintained.[11] Since the magnetic trackers weren't suitable for outdoor use, we developed a registration method with a high precision fiber-optic gyroscope and vision-based registration. This method showed precise registration performance even after one hour of use.

What dreams may come with MR technologies

The MR Project recreated a new age of VR, and brought the technology from the level in the lab to a level that could be used in our daily life. MR is a promising technology for application fields such as medicine and welfare, architecture and urban planning, and education and training. Entertainment industries also show great interest in MR. At MiRai-01, officials of museums and other visitor centers became advocates of MR. Some officials said that MR technology has the potential to drastically change the way we see exhibits. The sidebar "MR Attractions" (on page ??) introduces some systems near completion, each of which we designed for a specific application.

Since the concept of merging physical and cyberspaces covers applicable fields to a great extent, we expect that the interest or attention now paid to MR will spread and increase. Undoubtedly, more cyberspaces will come into our lives. If so, the MR technology that incorporates such cyberspaces with real life will be more important than ever. To satisfy all the requirements and requests on such demands, we have a lot of things to study not only in theory but also in experimentals.

Although we completed the MR Project in March 2001, almost all of the members of the project returned to Canon, where they continue their research and development of MR. Now we're developing a commercial package called MR Platform, consisting of a video ST-HMD and a software development kit for AR that we developed through the MR Project. ■

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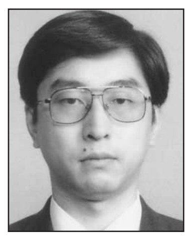

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